UNIVERSITY OF TOKYO

LOOKING AT THE STARS:
UNPACKING THE DEVELOPMENT OF ASTRONOMY IN CHILE

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ABBREVIATIONS

ACT	Atacama Cosmology Telescope
AIUC	Center for Astro-Engineering
ALMA	Atacama Large Millimeter/Submillimeter Array
APEX	Atacama Pathfinder Experiment
ATLASGAL	APEX Telescope Large Area Survey of the Galaxy
AURA	Association of Universities for Research in Astronomy
CASSACA	Chinese Academy of Sciences South America Center for Astronomy
CATA	Center for Excellence in Astrophysics and Associated Technologies
CCAT	Cornell Caltech Atacama Telescope
CEFOP	Center for Optics and Photonics
CLASS	Cosmology Large Angular Scale Surveyor
CMM	Center for Mathematical Modeling
CNTAC	Chilean Telescope Allocation Committee
CONAMA	Ministry of the Environment
CONICYT	National Commission for Scientific and Technological Research
CTIO	Cerro Tololo Inter-American Observatory
E-ELT	European Extremely Large Telescope
ESO	European Southern Observatory
FIDEOS	Fiber Dual Echelle Optical Spectrograph
FONDAP	Fund for Financing Research Centers of Excellence
FONDECYT	National Fund for Science and Technological Development
GMT	Giant Magellan Telescope
ISI	Import-substitution industrialization
LSST	Large Synoptic Survey Telescope
MCSS	Millennium Center for Supernova Science
ML	Millimeter-Wave Laboratory
NLHPC	National Laboratory of High-Performance Computing
OPCC	Office for the Protection of the Skies in Northern Chile
PIA	Associative Research Program
RAIG	Radio Astronomical Instrumentation Group
SPEL	Space and Planetary Exploration Laboratory
SOCHIAS	Union of Professional Astronomers
SUCHAI	Satellite of the University of Chile for Aerospace Investigation
TAO	Tokyo Atacama Observatory
VLT	Very Large Telescope

1. INTRODUCTION

The night of our homeland
Peppered with stars
In the divine sieve
Is straining the souls …

So much fervor has the sky
So much it loves, so much it gives
That sometimes I love
The night more than the day.
—Gabriela Mistral, "Andean Night"

The works of Gabriela Mistral, a Chilean poet who became the first Latin American writer to receive the Nobel Prize for Literature,[1] were deeply inspired by the majestic Andean mountain ranges and the clear night skies that surrounded the Chilean countryside. The dark and transparent skies of Chile showcase the magnificence of the Milky Way Galaxy and unlock the windows to the infinite depth of the universe. The Nobel Laureate was not the only one that was inspired by the splendor of Chilean skies, however. Since the mid-19th century, Chile's skies have attracted many astronomers and observatories from across the globe, all aiming to explore the heavens and to unravel the universe's hidden secrets. With the boom in construction of world-class telescopes since the mid-1900s, Chile has seen a rise in the number of projects being implemented in the Southern Cone country, as well as an expansion of its local astronomical community. At present, Chile is home to over a dozen major observatories and astronomical facilities and has also been selected to host a number of the world's most ambitious projects, including the Atacama Large Millimeter/Submillimeter Array (ALMA), Giant Magellan Telescope (GMT) and the European Extremely Large Telescope (E-ELT). It is estimated that, by the year 2020, Chile will concentrate 70% of the world's viewing capacity, with investments of over US$6 billion pouring into the country to

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[1] Nobel Prize, "Gabriela Mistral – Biographical," http://www.nobelprize.org/nobel_prizes/literature/laureates/1945/mistral-bio.html.

develop these state-of-the-art telescopes.[2]

With the international observatories and projects cementing Chile's reputation as an "astronomer's paradise,"[3] Chile has recently emerged as a major player in the field of observational astronomy. This phenomenon is frequently elucidated as an outcome of Chile's natural conditions: its exceptionally clear skies—which are cloudless for more than 300 days a year—and little atmospheric turbulence make Chile an ideal location for producing images from ground. To a great extent, Chile has been fortunate in possessing these natural conditions to be able to attract scientific infrastructure and talented astronomers from abroad. Though it is undeniable that these environmental circumstances have had a tremendous impact on the development of astronomy in Chile, a deeper look into the phenomenon reveals a series of collaborations, initiatives and state-led policies that catalyzed the advancement of astronomical studies. The various actors of Chilean astronomy have shown collaborative and strategic efforts to further the country's research capacity and to build an institutional structure to promote astronomical endeavors. This paper, thus, moves beyond the one-dimensional analysis of the relationship between Chile's geographical conditions and the development of its astronomy program and explores the often-overlooked feature of Chilean astronomy to provide a more comprehensive insight into the policies and collaborative mechanisms that paved the path for the country's astronomical progress.

In order to do so, the paper will first present an overview of Chile's astronomy program, followed by a review of existing scholarship on the development of science and technology in Latin America. This investigation will then examine how 1) the collaborative

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[2] CONICYT, "Astronomy, Technology, Industry: Roadmap for the Fostering of Technology Development and Innovation in the Field of Astronomy in Chile," 2012: 3; Michele Catanzaro, "CHILE: Upward trajectory," *Nature* 510 (2014): 204-5; Paula Leighton, "Chile 'not benefitting enough from big astronomy,'" *SciDev Net*, August 27, 2014, http://www.scidev.net/global/engineering/news/chile-not-benefitting-enough-from-big-astronomy.html.

[3] Gideon Long, "Why Chile is an astronomer's paradise," *BBC News*, July 11, 2011, http://www.bbc.com/news/world-latin-america-14205720.

structure of astronomical communities both within and outside of Chile and 2) the convergence between state-led policies and local scientific demands contributed to the development of astronomy in the Southern Cone country. This paper will then conclude by discussing the study’s theoretical and policy implications on Chile’s trajectory in astronomical studies.

2. OVERVIEW OF CHILEAN ASTRONOMY

1. Selecting Observational Sites in Chile

1.1 *Selecting Optimal Observatory Sites*

Since the beginning of modern astronomy, scientists have looked all across the planet for optimal sites for observing the universe. Selecting sites for the construction of observatories, however, is a long, arduous process that involves examining potential locations and weighing the pros and cons of each site. The general criteria for site selection evaluates whether the location is free of light or radio pollution; has calm and predictable atmospheric flow with a low cloudiness rate; has a relatively small effect on the surrounding ecological environment; provides adequate safety for people, machinery and equipment; and has a stable political environment. Observatory sites must also be located at high altitudes or, more precisely, above the *inversion layer*, which is a stratum in the atmosphere that has strong variations in temperature and wind movement. These sites are mostly found in the subtropics—between 20° and 35° latitude in both hemispheres—that are surrounded by water, such as Mauna Kea in Hawaii and La Palma of the Canary Islands. Observatories are also commonly situated on smooth planes at high altitudes above sea level with weak upper winds, as demonstrated by the astronomical site tests conducted in the Sonoran Desert of the United States, southwestern Africa and in the northern regions of Chile.[4]

1.2 *Choosing Chile: The Atacama Desert*

Chile, a narrow strip of land with a coastline of over 6,000 km, is wedged between the

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[4] Pierre-Yves Bely, Carol Christian, and Jean René Roy, *A Question and Answer Guide to Astronomy* (Cambridge: University Press, 2010), 233; Jingquan Cheng, *The Principles of Astronomical Telescope Design* (New York: Springer, 2009), 32; Hannu Karttunen et al., *Fundamental Astronomy* (New York: Springer, 2007), 47; Charles Liu, *The Handy Astronomy Answer Book* (Michigan: Visible Ink Press, 2008), 253-4; Günter D. Roth, *Handbook of Practical Astronomy* (New York: Springer, 2009), 565.

Pacific Ocean and the Andes, and it comprises an array of climates and geographical features: in the south, Chilean Patagonia boasts glaciers and granite peaks, while the arid Atacama Desert dominates the landscape in the north. These diverse climatic zones, as well as Chile's 15 administrative divisions, are shown below in Figure 2.1. As researchers began to realize in the 1800s, and more so in mid-20th century, the conditions in the northern part of Chile proved to be extremely favorable for observational astronomy. The Atacama Desert, one of driest regions of the world, experiences cloudless skies all year round, and in some parts of the desert, rainfall has never been recorded. Moreover, the cold Humboldt Current that flows northward from Antarctica along Chile's coast creates a pronounced inversion layer that minimizes atmospheric turbulence. Atacama's high altitude also contributes to superb observing conditions, especially for radio telescopes: the dry Atacama air—which thwarts water vapor in Earth's atmosphere from distorting infrared wavelengths from outer space—enables astronomers to clearly detect objects and movements in the sky.[5] Perhaps even more critical to astronomers, Chile's location in the southern hemisphere provides a clear view of the southern sky, which is largely invisible from countries north of the equator. Many celestial objects—such as the Magellanic Clouds and the globular cluster Omega Centauri—are precluded from observations conducted in the United States and Europe.[6] As mentioned briefly before, political stability also plays an essential role in the selection of observatory sites. Despite the military regime that held control of Chilean politics from 1973, Chile's return to democracy in 1990 marked its emergence as one of the most stable and prosperous countries in Latin America.[7] Chile's stable political economy, along with its excellent

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[5] Victor M. Blanco, "Telescopes, Red Stars, and Chilean Skies," *Annual Review of Astronomy and Astrophysics* 39 (2001): 6-7; W. Patrick McCray, *Giant Telescopes: Astronomical Ambition and the Promise of Technology* (Cambridge: Harvard University Press, 2004), 238.

[6] Renato Dicati, *Stamping Through Astronomy* (New York: Springer, 2013), 302; Govert Schilling, "An Astronomer's Paradise, Chile May Be the Best Place on Earth to Enjoy a Starry Sky," *Smithsonian Journeys Quarterly*, July 22, 2015, http://www.smithsonianmag.com/travel/star-trekking-chile-astronomy-180955798/?no-ist.

[7] Long, "Why Chile is an astronomer's paradise."

geographical features, has made it possible for international organizations to build their astronomical research centers in the region.

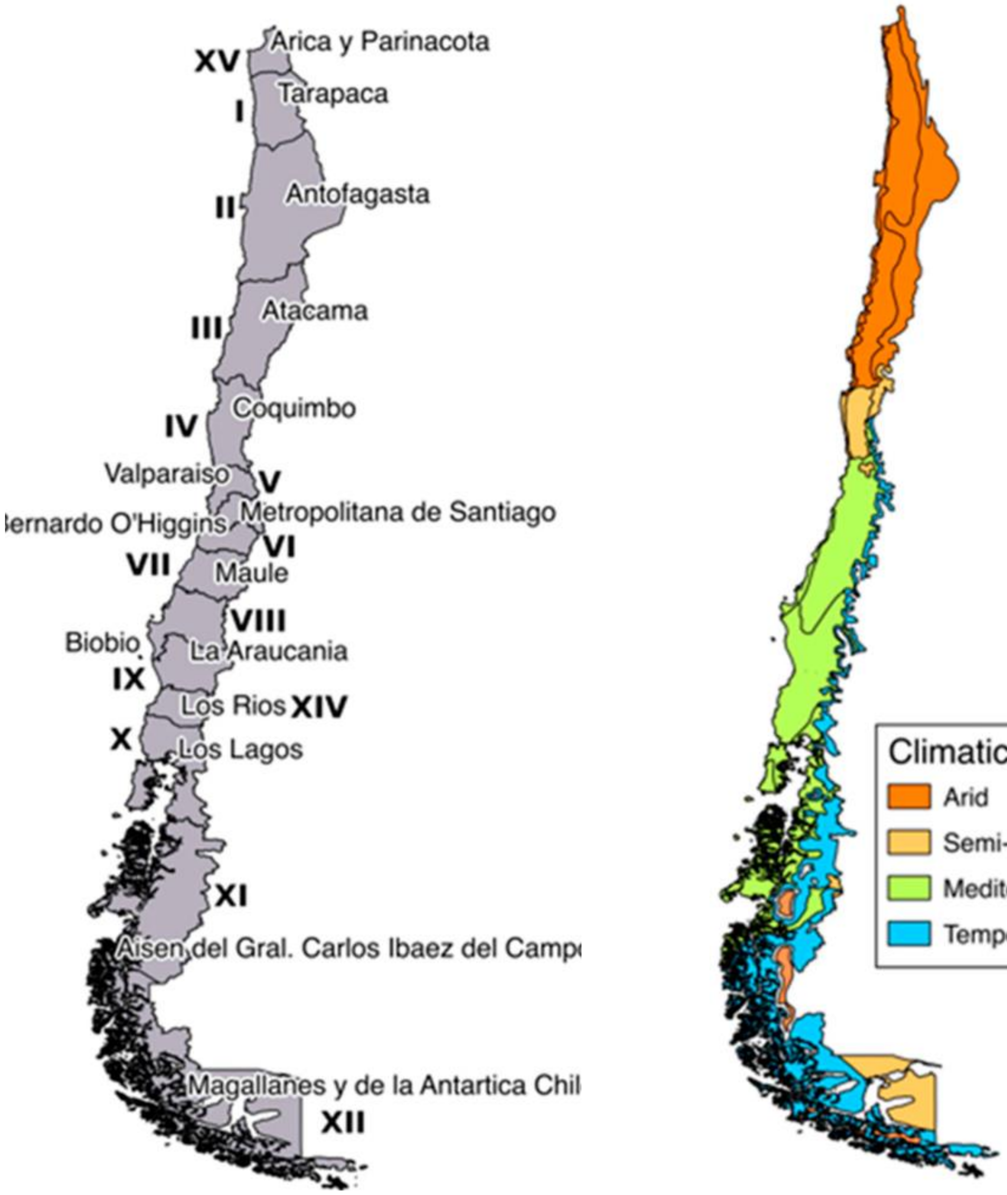

Figure 2.1. Administrative and climatic regions of Chile

Source: Douglas Aitken et al., “Water Scarcity and the Impact of the Mining and Agricultural Sectors in Chile,” *Sustainability* 8 (2016): 1-18.

2. Development of Observatories in Chile

Observatories, or facilities where astronomical observations take place, first appeared in the 18th century in a number of European cities—such as Berlin, Stockholm, Lund and

Turin—and were usually associated with universities. The momentum for the construction of observatories picked up in the 19th century in continental Europe and across the Atlantic in the United States, when both universities and private actors began funding the establishment of these facilities. In the United States, for example, the U.S. Naval Observatory in Washington, D.C. became the first observatory to be built in 1842. However, all of these newly-constructed observatories were typically built near cities, which produced poor-quality images due to urban light pollution and atmospheric turbulence. In addition, these major observatories were located in the northern hemisphere, which meant that there was a severe lack in observations made from the southern hemisphere. Although some expeditions were made to conduct observations in sites located south of the equator, by 1960, only a handful of observatories were located in the southern hemisphere, and these telescopes had only a fraction of the light-collecting power of those in the north.[8]

In order to receive higher-quality images of celestial objects and to observe the universe from the southern hemisphere, extensive astronomical site surveys were conducted in South Africa, Australia, Argentina and Chile by Yale, Columbia, Universidad de Chile and the European Southern Observatory (ESO) in the 1950s. ESO functions as a system of astronomical facilities run by a consortium of European states, and, as its name implies, its observing facilities are located in the southern hemisphere—especially in northern Chile.[9] A decisive figure that persuaded these American and European researchers to select sites in Chile was Professor Federico Rutllant from Universidad de Chile, who visited the United States in 1958 to discuss the possibility of U.S.-Chile collaborations for building and operating an astronomical observatory in the Southern Cone country. Because paved roads were a rarity in northern Chile at the time, the teams of American and European researchers

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[8] Bely, Christian, and Roy, *A Question and Answer Guide*, 204; Roger Leiton, “Increasing the Chilean Awareness of Dark-Sky Preservation,” in *Light Pollution: The Global View*, ed. Hugo E. Schwarz (Berlin: Kluwer Academic Publishers, 2003), 196; McCray, *Giant Telescopes*, 238.

[9] Liu, *The Handy Astronomy Answer Book*, 255.

explored the northern region in the form of horseback expeditions, which took them on long journeys to the summits of mountains like Cerro Tololo, Cerro La Silla and Cerro Las Campanas. Following the extensive surveys, the American team under the Association of Universities for Research in Astronomy (AURA) selected Cerro Tololo—a 2,200-m high mountain in the foothills of the Andean cordillera and approximately 500 km north of the Chilean capital, Santiago—and began the five-year process of constructing the Cerro Tololo Inter-American Observatory (CTIO) in 1962.[10] Telescopes sprouted on Cerro Tololo in the following decades. The observatory's future appeared even brighter when Chilean President Eduardo Frei and U.S. President Lyndon B. Johnson jointly announced, in 1967, that the National Science Foundation (NSF) and the Ford Foundation would fund the development of the largest telescope in the southern hemisphere.[11] The Carnegie Institution of Washington also installed the Las Campanas Observatory. ESO, on the other hand, purchased the 2,400-m ridge of Cerro Chinchado in the Coquimbo Region and inaugurated the La Silla Observatory in 1965.[12]

Since the establishment of Cerro Tololo, Las Campanas and La Silla in the 1960s, a number of new international observatories and telescopes has been constructed in Chile, and many projects have been carried out using these facilities. Between 1990 and 2000, ESO developed the Paranal Observatory, and the Carnegie Institution of Washington—together with private university partners—built the first sets of Magellan telescopes that were then installed at Las Campanas. Furthermore, in January 2002, the Gemini South Telescope was officially inaugurated; the following year in 2003, the ESO-operated Atacama Pathfinder Experiment (APEX)—which is currently the largest submillimeter-wavelength telescope

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[10] Blanco, "Telescopes, Red Stars, and Chilean Skies," 6; Dicati, *Stamping Through Astronomy*, 302; D. Lorenzen, "Jürgen Stock and His Impact on Modern Astronomy in South America," *Revista Mexicana de Astronomía y Astrofísica* 25 (2006): 75; Schilling, "An Astronomer's Paradise."

[11] McCray, *Giant Telescopes*, 238-9.

[12] CONICYT, "Astronomy, Technology, Industry," 35-9.

operating in the southern hemisphere—was installed in Llano de Chajnantor of the Atacama Desert; and in 2009, the Tokyo Atacama Observatory (TAO) was installed by the University of Tokyo also in Llano de Chajnantor. The chronology of major developments in Chilean astronomy is presented in Appendix A. In addition, a few other major facilities are currently under construction. The first is the Atacama Large Millimeter/Submillimeter Array (ALMA), which will be one of the highest and largest ground-based observatories in the world after completion. Plans to build the Giant Magellan Telescope (GMT) are also underway, along with the construction of the European Extremely Large Telescope (E-ELT), which would be the largest and most powerful optical/near-infrared telescope ever built.[13] These observatories and telescopes are described in further detail in Appendix B.

3. Growth of Chilean Astronomy

3.1 *Universities with Astronomy Programs*

In time for the completion of the Cerro Tololo, Las Campanas and La Silla observatories in the mid-1960s, Universidad de Chile created the country's first Astronomy Department under the Faculty of Physical Sciences and Mathematics in 1965. The first generation of undergraduate students from this Astronomy Department was able to continue with their postgraduate studies abroad with fellowships provided by American organizations that operated observatories in Chile. Las Campanas Observatory, for example, provided Carnegie fellowships to Chilean students to pursue further studies in astrophysics and astronomy until 2000. Approximately a decade after the establishment of its Astronomy Department in 1976, Universidad de Chile founded its Master's Degree program in

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[13] CONICYT, "Astronomy, Technology, Industry," 35-9; Schilling, "An Astronomer's Paradise."

astronomy.[14]

Up until this point, Chile's academic institutions seem to demonstrate a rather sluggish development of astronomy programs; yet, since the 1990s, Chile saw an expansion of institutions offering undergraduate and postgraduate programs in astrophysics and astronomy. Universidad Católica del Norte first launched its Astronomy Institute in 1996. Pontificia Universidad Católica de Chile—which had established and operated an astronomy group since 1980—also inaugurated its Astronomy and Astrophysics Department in 1996, which began to offer its undergraduate program in astronomy in 1999 and Master's and Doctorate courses in 2003. In 1999, Universidad de Chile created its PhD program in astrophysics; during the same year, Universidad de Valparaíso introduced its undergraduate program where students in the physics department can choose their concentration in astronomy. At the turn of the century in 2001, Universidad de La Serena opened its undergraduate program in physics with a minor in astronomy.[15] Universidad Andrés Bello also followed suit by launching its undergraduate program in astronomy in 2011 and its PhD program in 2014.[16] Moreover, in 2013, Universidad Diego Portales formed its Astronomy Nucleus under the Faculty of Engineering.[17]

3.2 *Number of Chilean Astronomers*

As a result of the expansion of astronomy programs in universities across the country, Chile has experienced an "inflationary period" of astronomers in the last decade.[18] As shown below in Table 2.1, astronomers in Chilean institutions—which include professors, researchers and postdoctoral researchers—increased almost fourfold between 2005 and 2016.

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[14] CONICYT, "Astronomy, Technology, Industry," 35-9.

[15] Ibid, 35-9.

[16] Matías Gómez, interview by author, April 6, 2016.

[17] Keiichi Ohnaka, interviewed by author, April 13, 2016.

[18] Ezequiel Treister, interviewed by author, April 6, 2016.

The number of Chilean doctorate, master's and undergraduate students pursuing their degrees in astronomy also multiplied significantly during the same period, as indicated in Table 2.2. Whereas there were only 40 students of astronomy in 2005, the number grew to a total of 675 in 2016.

Table 2.1. Astronomers in Chilean institutions

	2005	2009	2013	2016
Professor	40	52	75	103
Researcher	0	0	0	11
Postdoctoral Researcher	19	44	73	107
Total	59	96	148	221

Source: Sociedad Chilena de Astronomía, "Censos de astrónomos en instituciones chilenas," 2016, http://www.sochias.cl/info/miembros/censos-de-astronomos.

Table 2.2. Students of Astronomy in Chilean institutions

	2005	2009	2013	2016
Doctorate	21	35	50	72
Master's	19	28	79	74
Undergraduate	0	456	530	529
Total	40	519	659	675

Source: Sociedad Chilena de Astronomía, "Censos de astrónomos."

It should be stressed that this rapid expansion of astronomical community represents a remarkable progress, especially considering Chile's weak science tradition. From a macro point of view, Chile has a highly-educated population and characterizes a country with a solid knowledge base: the coverage of primary education is almost universal, secondary attainment rates have increased rapidly and 29% of the adult population has tertiary education—a share that exceeds the percentage of the EU-28 (27%).[19] Nonetheless, Chile's science community continues to remain small. In the latest dataset available, Chile had less than one researcher per thousand employees (0.95), compared to the European Union's average of seven.[20]

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[19] OECD, *Maintaining Momentum: OECD Perspectives on Policy Challenges in Chile* (Paris: OECD Publishing, 2011), 64; OECD, *OECD Science, Technology and Industry Outlook 2014* (Paris: OECD Publishing, 2014), 288.

[20] OECD, *OECD Science, Technology and Industry Outlook*, 288.

Furthermore, the number of scientific and technical journal articles (per billion PPP$ GDP) that Chilean researchers published in 2013 was only 17.07. The citable documents H index—which is the economy's number of published articles (H) that received at least H citations in the period from 1996 to 2013—was 194, which shows significant disparities with Germany (740), the United Kingdom (851) and the United States (1,380).[21]

3.3 *Paper Publications by Chilean Astronomers*

According to the data available on Web of Science, the volume of academic papers published in astronomy is the second largest after those published under clinical science. Yet, as shown below in Table 2.3, citation rates for articles published by astronomers are significantly higher than those published by researchers in all other fields. Whereas the total

Table 2.3. Paper and cites by research field

	Research Fields	Web of Science Documents	Cites	Cites/Paper
1	Space science	6,120	137,952	22.54
2	Clinical medicine	7,085	73,644	10.39
3	Physics	4,089	44,313	10.84
4	Plant & Animal science	5,168	34,338	6.64
5	Chemistry	4,289	33,061	7.71
6	Biology & Biochemistry	3,053	32,759	10.73
7	Environment / Ecology	2,985	31,853	10.67
8	Geosciences	2,148	27,104	12.62
9	Molecular biology & Genetics	1,124	25,837	22.99
10	Engineering	3,045	19,742	6.48
11	Agricultural science	2,754	19,147	6.95
12	Neuroscience & Behavior	1,321	17,663	13.37
13	Social sciences	3,390	11,459	3.38
14	Immunology	1,118	11,132	9.96
15	Mathematics	2,448	11,044	4.51
16	Pharmacology & Toxicology	847	8,669	10.23
17	Microbiology	650	6,580	10.12
18	Psychiatry / Psychology	1,094	6,403	5.85
19	Materials science	1,031	6,327	6.14
20	Computer science	1,071	4,180	3.9
21	Economics & Business	1,218	4,104	3.37
22	Multidisciplinary	32	381	11.91

Source: Web of Science.

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[21] Soumitra Dutta, Bruno Lanvin, and Sacha Wunsch-Vincent, *The Global Innovation Index 2014: The Human Factor in Innovation* (Geneva: World Intellectual Property Organization, 2014).

number of citations in space science is 137,952, the number of citations for articles in clinical medicine trails behind at 73,644.

Furthermore, the number of Chilean publications in astronomy has risen considerably during the past decade. The total number of papers nearly doubled from 1,979 to 3,642 from 2005 to 2015. Along with the rise in publications, the total number of citations also increased during the same time period, from 22,829 to 51,350 citations. Tables 2.4 and 2.5 illustrate the trends in publications and citations in Chilean astronomy.

Table 2.4. Publication and citation trends in astronomy

	2005-2009	2006-2010	2007-2011	2008-2012	2009-2013	2010-2014	2011-2015
Total papers	1,979	2,133	2,299	2,521	2,854	3,277	3,642
Total citations	22,829	26,405	28,733	30,091	35,845	43,451	51,350
Total citations/ paper	11.54	12.38	12.50	11.94	12.56	13.26	14.10

Source: Web of Science.

Table 2.5. Publication and citation trends in astronomy (normalized)

	2005-2009	2006-2010	2007-2011	2008-2012	2009-2013	2010-2014	2011-2015
Total papers	100%	108%	116%	127%	144%	166%	184%
Total citations	100%	116%	126%	132%	157%	190%	225%
Total citations/ paper	100%	107%	108%	103%	109%	115%	122%

Source: Web of Science.

4. Development of Chilean Astronomy: Comparative Perspective

As indicated above, Chile has cultivated its astronomical community and has gradually cemented its prominence in international astronomy in the last ten years. Considering this Chilean example, one may question whether the development of such "niche" sector is unique to the Southern Cone country or is, in fact, a rather unexceptional phenomenon in the emerging economies of Latin America. As it happens, the region has seen an emergence of a few pockets of scientific excellence in the recent years. One prominent example is Argentina's research in alternative RNA splicing, a complex process that involves the generation of multiple proteins by a single gene. The frontrunner of this Argentinian development, molecular biologist Dr. Alberto Kornblihtt, discovered one of the first cases of this process in humans while he was completing his postdoctoral fellowship abroad; he moved back to Buenos Aires soon after and assembled a group of researchers—the Kornblihtt Lab—that continues to explore this field of study. Under his supervision, a number of doctoral students and postdoctoral fellows have published notable works on alternative splicing. Researchers in the field have also established a small community of "RNArgentinos," which have for years organized informal seminars and meetings to share data, ideas and techniques.[22] Despite the contributions of the Kornblihtt Lab to the development of this niche sector, it has yet to reach the magnitude of Chile's astronomy program. Unlike astronomy in Chile, advancements in alternative RNA splicing has not led to an expansion of molecular biology programs in Argentinian universities, nor has it induced a noticeable increase in the number of biologists and their contributions to existing literature in the field. The Argentinian case also has not entailed institutional changes to further promote research in molecular biology—such as domestic and international collaboration mechanisms and government-initiated policies—unlike in Chile, as will be elaborated in greater detail in the following sections. It is perhaps safe to suggest, thus, that the development of astronomy in Chile presents an exceptional case where an emerging, middle-income country in Latin America has successfully fostered its niche field in science.

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[22] Aleszu Bajak, "Argentina: The RNA sleuths," *Nature* 510 (2014): 204-206; Universidad de Buenos Aires, "The Kornblihtt Lab," http://ark.fbmc.fcen.uba.ar/home_eng.php.

3. LITERATURE REVIEW

Despite the rapid development of Chile’s astronomical capacity, much of the literature on the development of science and technology in Latin America delves into the mechanisms behind the region’s lack of progress in fostering a culture of innovation. This lag has often been explained, in an oversimplified manner, as the product of the region’s poverty and lack of qualified human resources, low investment levels in science and technology, absence of a science tradition, inefficient governance, to name a few. To an extent, these explanations are valid and highlight the obstacles that the region faces in boosting endogenous scientific activities. They do not, however, explicate how these hurdles have been instituted nor why Latin America continues to be characterized as a region with little scientific and technological growth.

Instead of singling out obstacles that the region has historically—and continues to—face and equating them as explanations of its limited contributions to science, the panorama should be situated within the scope of Latin America’s political economy. In Latin America, the development of science and technology has been deeply embedded in the global economic structure. Scientific progress has also been influenced by government-defined roles that scientific and technological developments should play within these economic structures. The following three schools of thought delineate how economic structures have shaped scientific progress in Latin America. The first line of scholarship posits that global and domestic economic circumstances configured a new form of dependency, where Latin America—which produces low-knowledge goods with little added value—takes its place as a peripheral actor in the global economy. The second school of literature argues that Latin American governments’ embracing of the linear model of innovation contributed to the infrastructural partiality of the region’s scientific community. Lastly, the third school of thought postulates that the divergence of explicit and implicit policies in formulating science policies has hampered the region's scientific and technological progress.

1. Core-Periphery Model: Latin American Dependency on Foreign Science

1.1 *The Era of Import Substitution Industrialization (ISI)*

During the period of outward growth from 1850 to 1930, Latin American economies were based on exporting primary commodities with little intellectual value added—such as Brazilian coffee, Chilean copper and Argentinian cattle—and importing manufactured goods.[23] Reflecting the core-periphery model of the global system, Latin America during this time period attained a peripheral insertion in the international economy. Following the stock market crash in 1929, demand for Latin American commodities fell as consumption and investment sharply declined; prices for commodities plummeted, along with government revenues from export. The supply of manufactured goods from industrialized countries was also disrupted due to the onset of World War II and the diversion of production into wartime manufacturing. The severe shock of the Great Depression, consequently, pushed peripheral countries in Latin America to look inward for sources of economic growth, to transform their economic structure by reducing their dependency on the core countries and to embrace the process of import-substitution industrialization (ISI). Characterized by excessive protection of domestic industries, indiscriminate subsidy programs and creation of state-owned enterprises, ISI aimed to support the initiation of local manufacturing to take place of the imports.[24]

It is important to highlight the implications that ISI had on the development of science

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[23] Rodrigo Arocena and Judith Sutz, "Latin American Universities: From an original revolution to an uncertain transition," *Higher Education* 50 (2005): 585; Hebe Vessuri, "The universities, scientific research and the national interest in Latin America," *Minerva* 24 (1988): 7.

[24] Renato Dagnino, Hernán Thomas, and Amílcar Davyt, "El pensamiento en ciencia, tecnología y sociedad en Latinoamérica: una interpretación política de su trayectoria," *Redes* 3 (1996): 17; Helio Jaguaribe, "Por qué no se ha desarrollado la ciencia en América Latina," in *El pensamiento latinoamericano en la problemática ciencia-tecnología-desarrollo-dependencia*, ed. Jorge A. Sabato (Buenos Aires: PLACTED, 2011), 111; Peter Kingston, *The Political Economy of Latin America: Reflections on Neoliberalism and Development* (New York: Routledge, 2011), 25-44.

and technology in Latin America. On one hand, ISI set in place conditions for the expansion of local industries and technological facilities for the production of goods and services. On the other hand, ironically, the state-led strategy configured a mechanism where Latin American countries became even *more* dependent on foreign science and technology for the production of these goods and services. This second point merits a more thorough explanation. As posited by Dagnino, Thomas and Davyt (1996) and Jaguaribe (1971), the process of ISI pushed governments to produce manufactured goods to substitute those that were formerly imported from the core industrialized countries; yet, existing technologies in Latin America were limited and insufficient to meet the consumer demands of the Latin American population. As a result, governments needed to welcome scientific and technological imports from the core countries in order to produce sufficient goods and to meet the continent's consumer demands. This meant that there was little need for major innovative activities to amplify and diversify the local scientific knowledge base, and, in most cases, the technologies imported from the core countries were only imitated and modified without the application of major technological changes.[25]

1.2 *Neoliberalism, Globalization and Knowledge Asymmetry*

Decades under the ISI regime resulted in the exhaustion of inward growth and high debt and interest rates, which unraveled the devastating effects of the Latin American debt crisis. The 1980s in Latin America were characterized by stagnation of economic performance, severe struggles with inflation and debt, and decline in social figures. Following the so-called "lost decade" of the 1980s, a macroeconomic transformation was attempted under the neoliberal scheme. One of the key features of this macroeconomic policy was the opening of

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[25] Dagnino, Thomas, and Davyt, "El pensamiento," 18; Jaguaribe, "Por qué no se ha desarrollado la ciencia," 111-2.

the economies and the region's active reinsertion in the global economy. As a result of this abrupt exposure to international economic competition, Latin American economies once again began to rely on exporting goods with comparatively low-added value of knowledge.[26] As asserted by Arocena and Sutz (2005), the neoliberal strategy drove Latin America towards a "neo-peripheral" reinsertion in world trade and, ultimately, towards a process of "de-industrialization."[27]

With the globalization of markets for goods and services and the expansion of neoliberal schemes, Castells (1996) argues that there has been "a deeper transformation in the structure of trade." As the knowledge component of goods and services becomes more decisive in terms of value added, a new form of global imbalance between countries that produce high-knowledge goods and those that export low-knowledge products is superimposed.[28] In this knowledge-based global economy—where scientific capacity and technological infrastructure are key to international competitiveness—Sunkel (1970) and Vessuri (1988) maintain that a new core-periphery model has emerged, institutionalizing a hierarchical division of labor between knowledge-based producers and the technologically-dependent economies.[29] This means that, according to Kreimer (2007), lesser developed regions are subject to a dependence relationship of knowledge, particularly scientific and technological, produced in industrialized countries.[30] Although globalization and international trade do open up new channels of integration of newly industrializing economies like Latin America, this integration process has been uneven and has exacerbated the

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[26] Kingston, *The Political Economy*, 45.

[27] Arocena and Sutz, "Latin American Universities," 1224.

[28] Manuel Castells, *The Rise of the Network Society* (West Sussex: John Wiley & Sons, 2010), 108-124.

[29] Osvaldo Sunkel, "La universidad latinoamericana ante el avance científico y técnico; algunas reflexiones," in *El pensamiento latinoamericano en la problemática ciencia-tecnología-desarrollo-dependencia*, ed. Jorge A. Sabato (Buenos Aires: PLACTED, 2011), 125-8; Vessuri, "The universities," 3.

[30] Pablo Kreimer, "Social Studies of Science and Technology in Latin America: A Field in the Process of Consolidation," *Science, Technology & Society* 12 (2007): 1-2.

knowledge asymmetry and economic cleavage between developed countries and those grouped under the vague notion of "the South."[31]

1.3 *Neo-Dependency Theory*

The limited development of scientific capacity in Latin America has been deeply interrelated with the dynamics of the global economy and state-led macroeconomic policies. Another takeaway is that, in Latin America, the central influence on scientific and technological practices has been the legacy of dependency that juxtaposes science at the "core" to that done at the "periphery." This long-standing dependency on imported capital goods and reliance on inflows of foreign know-how have retarded the development and diffusion of new scientific discoveries in Latin America.[32] Because a significant portion of scientific knowledge was imported from abroad, Bisang (1994) points out how, in Latin America, there has been "no endogenous process of local scientific forces."[33] Following this logic of dependency, Barandiaran (2015) further stresses that foreign science and technology—including telescopes and astronomical observatories—reproduce the hierarchical relations that keep Latin American countries dependent on expertise from the global North instead of fostering endogenous scientific activities.[34]

2. "Structurally Unachieved" System of Scientific Advancement

Following the end of World War II, significant effort was made in Latin America to build an institutional structure that would encourage the formation and effectiveness of active

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[31] Arocena and Sutz, "Latin American Universities," 584, 1225; Dagnino, Thomas, and Davyt, "El pensamiento," 31-2.

[32] Arocena and Sutz, "Latin American Universities," 1225.

[33] Roberto Bisang, "Industrialización e incorporación del progreso técnico en la Argentina," *Comisión Económica para América Latina y el Caribe* (1994): 6.

[34] Barandiaran, Javiera, "Reaching for the Stars? Astronomy and Growth in Chile," *Minerva* 53 (2015): 142-4.

scientists. Consequently, governments across the region aimed to establish a scientific and technological base in sectors considered to be strategically important for economic growth. These governments implemented state-led policies that targeted to internalize the linear chain of innovation from basic to applied research, followed by technological development, production and diffusion.[35] This linear model of innovation, as outlined by Bush (1945), conceptualizes scientific research as absorbing a homogenous, straightforward and unilateral flow of public investments and, consequently, expanding knowledge upon which future research activities will be able to draw.[36] This basic knowledge is also assumed to be automatically transferable to the industry sector: it can "be particularized as an array of specific technological capabilities that, under the right economic conditions, can generate innovations yielding lower cost or higher quality of new goods and services."[37] Deriving from this linear model, governments in Latin America during the 1950s and 1960s aspired to develop a reservoir of scientific knowledge within the limited scope of institutions involved in R&D activities, namely universities and research centers.

Because these governments aimed to strengthen scientific and technological development only within universities and research institutions, these state-led policies failed to integrate private actors and potential industrial users into the innovation scheme. Due to the governments' strong inclination to the linear model, the link between research and industry—which is essential for the application of scientific discoveries to the development of new technologies—was not institutionally developed. This means that there were little, if any,

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[35] Dagnino, Thomas, and Davyt, "El pensamiento," 22; Benoît Godin, "The Linear Model of Innovation: The Historical Construction of an Analytical Framework," *Science, Technology, and Human Values* 31 (2006): 640; Vessuri, "The universities," 31.

[36] Wiebe E. Bijker, *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change* (Cambridge: MIT Press, 1995), 7; Vannevar Bush, "Science: The Endless Frontier," *Science Education* 29 (1945): 218; Nathan Rosenberg, "Critical issues in science policy research," *Science and Public Policy* 18 (1991): 335-346.

[37] Philippe Aghion, Paul A. David, and Domonique Foray, "Science, technology and innovation for economic growth: Linking policy research and practice in 'STIG Systems,'" *Research Policy* 38 (2009): 682.

interactive links between academia and the various subsystems for scientific and technological production. As a result, high levels of basic science research achieved by universities were not transferred to other sectors for technological development. These academic institutions, thus, developed as isolated research enclaves without contributing to the national innovation systems.[38] Because there are little possibilities for universities to contribute to scientific development when there are no linking actors participating in the knowledge-articulation process, Arocena and Sutz (2001) contends that Latin American academia continues to function as a "lonely actor" regarding knowledge production.[39] Instead of cultivating scientific progress by integrating different actors of the innovation system, the policies implemented since the 1950s generated a mechanism that alienated academia from the innovation apparatus and private industry from other research-generating institutions.

It should be noted, however, that this "loneliness" of academic institutions does not mean that they have not made efforts to establish links with private actors. In fact, universities across Latin America have recently sought to foster relations with firms, such as through the establishment of technology-transfer offices. Yet, in almost all cases, the inefficiency of the university accountancy system encumbers the universities' efforts to cultivate relationships with private actors. Likewise, Arocena and Sutz (2011) underlines how universities are still ill-equipped to engage in "extensionism," that is, "to let the world outside the university know about what the university is able to produce and to take actions to promote the effective use of the university's capabilities." Oftentimes, technology-transfer offices wait for private clients to approach them instead of taking a more proactive stance, resulting in institutional sub-

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[38] Dagnino, Thomas, and Davyt, "El pensamiento," 22-3; Amílcar O. Herrera, "Los determinantes sociales de la política científica en América Latina: Política científica explícita y política científica implícita," in *El pensamiento latinoamericano en la problemática ciencia-tecnología-desarrollo-dependencia*, ed. Jorge A. Sabato (Buenos Aires: PLACTED, 2011), 155-6; Sunkel, "La universidad latinoamericana," 129-130; Vessuri, "The universities," 6.

[39] Arocena and Sutz, "Latin American Universities," 1229.

utilization.[40]

Other actors within Latin America's innovation system have also endeavored to establish the necessary "building blocks" for scientific and technological development. These building blocks include, for example, innovation incubators, tax incentives, and scholarships and prizes. However, akin to the situation in promoting university-industry linkages, there are missing institutions and mechanisms—such as sufficient technology-extension programs and seed capital—that fail to cultivate a scientific, knowledge-based community. Because of this "structurally unachieved character of the innovative organizational fabric,"[41] Latin America has struggled to foster a solid infrastructure of scientific activity that pulls together communication networks among relevant actors in the scientific community.[42]

3. Divergence of Explicit and Implicit Policies

According to Herrera (1973), scientific and technological development is a product of interplay between *explicit* and *implicit* science policies. The former refers to an "official" policy that is expressed in governmental regulations and is commonly recognized as the science policy of the state. The latter, which presents a more arduous process to define, does not have a formal nor official function; rather, it embodies the society's scientific and technological consciousness. Implicit policy, in other words, represents the society's demands, necessities and priorities for scientific and technological advancement. Ideally, for scientific development and technological production to take place effectually, explicit and implicit policies need to show signs of conversion: the government-led explicit policy outlines strategies that that aim to bolster the scientific knowledge base, which is perceived to be socially relevant and important by the local scientific community.

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[40] Arocena and Sutz, "Latin American Universities," 1226.

[41] Ibid, 1229.

[42] Barandiaran, "Reaching for the Stars," 146.

In Latin America, however, divergence between explicit and implicit science policies has been a more common reality than policy convergence. As mentioned in the previous section, during the 1950s and 1960s, governments across the region aspired to build an institutional structure for increased scientific activities that had practical economic utility. Naturally, government support was directed at scientific and technological sectors judged to be economically and socially important. Yet, these state-led aspirations for national economic growth came into conflict with the demand for freedom in the choice of scientific inquisition. The goals and contents conveyed in explicit policies for scientific development, in other words, did not converge with the objectives and intellectual aspirations of local scientists. Vessuri (1988) illustrates this divergence by providing an analysis of the Brazilian example. Throughout the 1960s, the Brazilian government provided funding and institutional support for universities and academic centers for research in science and technology. Yet, since the beginning of 1970s, the state began to pursue a new direction in resource allocation that primarily benefited state-run firms like Petrobras, a multinational corporation engaged in the petroleum industry.[43] The break in funding for universities represented a sharp divergence between the government's explicit policy and the scientific aspirations of Brazil's science community.

The pervasiveness of divergence between explicit and implicit policies is further exacerbated by the fact that the practice of science is skewed toward issues defined by technologically-advanced countries. As maintained by Castells (1996), Fressoli et al. (2014), Herrera (1973) and Vessuri (1988), there is fundamental asymmetry in the scientific issues taken up by research: problems that are relevant to developing countries "but offer little general, scientific interest, or do not have a promising, solvent market, are neglected in

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[43] Vessuri, "The universities," 14-28.

research programs of dominant countries."[44] Because of the difficulties in performing "rigorous" research that is pertinent to the regional context, a considerable portion of scientific research conducted in Latin America has little links with the necessities and priorities of the continent.[45]

4. Explaining the Development of Latin America's "Niche" Scientific Sectors

From existing literature, the development of science and technology in Latin America is characterized by dependency on knowledge-based economies, inadequate linkages between different research-generating actors, and divergence between state-led policies and societal demands. These elements have hindered the growth of scientific communities and national innovation systems across the continent—an impression on the innovative fabric that can still be felt today. But if the panorama painted by existing scholarship is theoretically valid, how has Latin America contributed to the development of "niche" sectors in science, such as astrophysics and observational astronomy in Chile?

As mentioned briefly above, the observatories and astronomical facilities that have recently cropped up in Chile can be expounded with the logic of dependency: they do not epitomize endogenous scientific progress in the Southern Cone country but, rather, reproduction of hierarchical relations that keep Latin American countries reliant on the scientific activities of the global North. The small astronomical community and weak linkages between the various actors in Chile's innovation system—a matter that will be described in greater detail in the following sections—also seem to reinforce the argument that Chilean astronomy is a manifestation of scientific and technological dependency. Moreover, regarding the notion of explicit and implicit policies, a divergence in the two types of policies can be

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[44] Castells, *The Rise of the Network Society*, 125.

[45] Herrera, "Los determinantes sociales," 153; Vessuri, "The universities," 4.

speculated. Local astronomers and astrophysicists may want to take advantage of the spectacular observational sites and fulfill their scientific aspirations; on the other hand, however, the Chilean government may not judge astronomy to be strategically relevant for macroeconomic growth.

Despite the potential validity of these arguments, Chile's increasing participation in the global network of observational astronomy can also be explained by taking the converse of the three schools of thought. What if Chile's astronomy program shows considerable progress precisely because it had been able to surmount the barriers outlined in the existing literature—the scientific dependence, weak innovation linkages, and discrepancy between explicit and implicit policies? The reasoning behind this converse once again stems from the dynamics of globalization. As Castells (1996) asserts, the international science community continues to maintain its asymmetrical character; yet, at the same time, it ensures communication between scientists, as well as the global diffusion of knowledge and technological know-how. Over time, this web of scientific knowledge creates a horizontal network of R&D that permeates sectors and countries. Hence, globalization and the uneven development of science and technology "de-localizes the logic of informational production from its country basis, and shifts it to … global networks."[46] This logic can be applied to the development of Chilean astronomy. Due to the expansive nature of the science community and technological know-how, Chilean scientists have been able to acquire a greater volume of knowledge and, consequently, contribute more to the field of astrophysics. Through this process of "de-localizing" informational production, Chilean astronomers gained a greater level of autonomy in producing scientific knowledge and contributing to the technological development of astronomical instruments, instead of depending on the knowledge generated in industrialized economies; began to cultivate stronger relationships with research-conducting and

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[46] Castells, *The Rise of the Network Society*, 124-9.

technology-developing actors in the astronomical community; and pushed for the conversion of explicit and implicit policies for the development of Chile’s astronomical capacity.

4. RESEARCH DESIGN

1. Structure of the Investigation

As elucidated in the previous section, existing literature on science and technology in Latin America underscore the effects that its peripheral insertion in the global economy, weak institutional infrastructure, and divergence between explicit and implicit policies had on the region's slow progress in fostering a culture of scientific innovation. Contrary to these prevailing ideas, Chile has succeeded in developing its astronomy program and in cementing its role in the international astronomical society. The Latin American country has successfully hosted a number of international observatories and ambitious astronomical projects, such as ALMA and E-ELT; inaugurated new astronomy programs in universities across Chile; and has expanded its pool of qualified researchers. The fundamental question of this research, thus, stems from the discrepancy between the overriding literature on scientific development in Latin America and the deviant case of Chilean astronomy: how has Chile achieved high levels of scientific development in the field of astronomy—an epitome of "big science"?

In order to answer this question, the investigation first explores the linkages between the various subsystems that have been cultivated in Chile for astronomical development, along with the mechanisms that these linkages created for knowledge transfer to local astronomical communities. These linkages will specifically focus on the partnerships that have been established between the three large Chilean universities—Universidad de Chile, Pontificia Universidad Católica de Chile and Universidad de Concepción—and foreign universities, research institutions, and international observatories. After analyzing these joint collaborations, this paper then assesses how these partnerships have enabled knowledge and technological knowhow to be transferred from international organizations to Chilean institutions. In line with Argote and Ingram (2000)'s broad definition of inter-organizational knowledge transfer, which “manifests itself through changes in the knowledge or performance of the recipient units,”[47] this paper operationalizes knowledge transfer as the initiatives that have been launched by Chilean universities independent of foreign institutions, as well as the research outcomes and technological developments that have formed as a result of these initiatives. The paper then surveys how scientific aspirations of Chilean researchers and state-led policies regarding observational astronomy have often coincided, steering the direction of collective scientific effort. This investigation aims to do so by assessing how the aspirations of local astronomers to transform astronomy into a leading scientific field in Chile have converged with the objectives of a number of government policies that have been implemented in the last several decades. By examining how Chile has established a “structurally *achieved*” system of astronomical research and reached a convergence point of explicit and implicit science policies, this paper aims to underscore Chile’s development of a strong astronomical community and increasingly autonomous system in conducting astronomical research.

2. Data Sources and Collection

Data on the development of Chilean astronomy was collected from secondary sources, such as published journal articles, investigation reports, government records, books and news articles. This data was also gathered from both English and Spanish sources. In addition to these secondary sources, in-depth interviews were conducted with a total of 12 astronomers, professors, and executive members from Chilean universities, astronomical societies, observatories, and international organizations that run and manage observatories in Chile. The list of interviewees and their affiliations are recorded below in Table 4.1. All interviews except for one with the Associate Professor of the University of Tokyo Atacama Observatory

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[47] Argote and Ingram, 151.

Project (TAO) were conducted via Skype or telephone.

Table 4.1. List of interviewees

	Affiliation	Position
1	Universidad de Chile *Department of Astronomy*	Professor
2	Pontificia Universidad Católica de Chile *Institute of Astrophysics*	Associate Professor
3	Pontificia Universidad Católica de Chile *Institute of Astrophysics*	Professor
	Chilean Astronomical Society (SOCHIAS)	President
4	Universidad Católica del Norte *Astronomy Institute*	Associate Professor
5	Universidad Andrés Bello *Department of Physical Sciences*	Professor
6	European Southern Observatory (ESO)	Representative in Chile
7	Associated Universities, Inc. (AUI)	Vice President for Science & Programs
8	Las Campanas Observatory	Director
9	Atacama Large Millimeter/Submillimeter Array (ALMA)	Science Operations Astronomer
10	University of Tokyo Atacama Observatory Project (TAO)	Associate Professor
11	Chinese Academy of Sciences South America Center for Astronomy (CASSACA)	Director, Research Professor
12	Cosmology Large Angular Scale Surveyor (CLASS)	Director

5. RESULTS

I. Linkages: Chile's Astronomy Program

With the rise in the number of astronomy and astrophysics departments available at Chile's universities, the astronomical community began to work in partnership with a number of foreign universities, research centers and observatories located in Chile. These collaborations have not only strengthened Chile's capacity in astronomical research, but have also encouraged local astronomers to gradually become involved in the process of developing instruments and devices for the international observatories. Yet, before delving into the linkages that Chilean institutions have developed with international astronomical organizations and overseas research centers, the historical progression of Chilean institutions should first be explored to paint the panorama of Chilean higher education.

1. Evolution of Chilean Higher Education

From the establishment of Universidad de Chile in 1842 until the educational reforms that were put into effect more than a century later in 1980, higher education in Chile had been funded and regulated by the national government. Because the provision of education for its population was considered to be under the responsibility of the state, Chile had often been described as an *estado docente,* which directly translates into a "teaching state." Prior to 1980, the Chilean higher education system was composed of eight universities—two public and six private—all of which were given direct subsidies by the public treasury. Financing of these institutions consisted largely of public incremental funding based on previous budget allocations and a distribution formula loosely arranged according to enrollment. Despite the homogenous funding scheme of these institutions—which later became known as *universidades tradicionales*, or "traditional universities"—the size of these universities varied considerably: the two public universities absorbed over 60% of all undergraduate students in the country, with Universidad de Chile representing the largest student population. In the progressive atmosphere of the 1950s and 1960s, however, all of the universities saw an expansion of their student population. University enrollment went from slightly over 20,000 in 1957 to 55,600 in 1967, and to over 146,000 students in 1973. Public funding for the universities also doubled during the time period to accommodate the increasing number of enrollees. Although funding came from the state, it is important to note that these eight universities exercised a high degree of autonomy regarding their institutional governance. Rectors, deans, and department directors were selected by the professors and faculty members of the universities. In some cases, these selection processes involved the participation of students. Universities were also entitled to freely initiate new departments and academic disciplines and extend professional titles and academic degrees.[48]

However, the effervescence of Chile's educational system came to an abrupt halt on September 11, 1973. Immediately following the coup d'état led by Augusto Pinochet against Salvador Allende's government, the military regime appointed new rectors for the eight traditional universities, who assumed all regulatory power that was previously distributed amongst various authorities in the higher education system. Under Decree Number 50 that was passed on October 2, 1973, these new rectors retained discretionary power over all decisions concerning university fees and the composition of university staff, cancelling the universities' self-governing powers. Faculty associations and student bodies were also prohibited. A long-standing tradition of institutional autonomy that was enjoyed by the

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[48] Barandiaran, "Reaching for the Stars," 145-6; Andrés Bernasconi, "Does the affiliation of universities to external organizations foster diversity in private higher education? Chile in comparative perspective," *Higher Education* 52 (2006): 307; Andrés Bernasconi and Fernando Rojas, "Informe sobre la Educación Superior en Chile: 1980-2003," *Digital Observatory for Higher Education in Latin America and the Caribbean* (2003): 17-9; José Joaquín Brünner, *Informe sobre la educación superior en Chile* (Santiago de Chile: Salesianos, 1986), 35.

universities could no longer be practiced under the strict surveillance of the military regime.[49]

Another major institutional impact that the authoritarian regime had on Chile's higher education system was the reduction in funding. As mentioned previously, prior to the 1973 coup, all of the eight universities were fully funded by the state. Yet, between 1974 and 1980, public spending on higher education fell drastically by 15% to 35%. Because these institutions were no longer able to rely on the state for funding, they were impelled to charge students with high tuitions to cover the necessary fees.[50] The Pinochet regime also aimed to downsize universities by eliminating certain academic disciplines and shrinking the number of places offered to incoming students. These places offered by the institutions declined from 100,000 during the 1972–1973 academic year to 85,599 in 1974–1975, and to 67,862 in 1976–1977. As a result, the total enrollment of university students fell from 145,000 in 1973 to 134,000 in 1976. Moreover, the educational reform under the military regime divided Universidad de Chile into 14 smaller units, primarily to control anti-governmental movements that were expected to arise from the largest academic institution in the country.[51]

Furthermore, professors, students and university officials associated with or showed sympathy for Allende's government were expelled from the institutions and, in a number of cases, were exiled, detained, tortured or assassinated.[52] Due to the lack of official statistics, it is difficult to determine the precise number of professors, students and staff that were expelled from universities following the military regime's intervention in 1973. Yet, Garretón and Pozo (1984) estimates that, during the early stages of the dictatorship, about 25% of professors across a range of disciplines, 10% to 15% of non-academic staff and 15% to 18% of students were dismissed from the eight universities. This means that a total of more than 20,000

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[49] Bernasconi and Rojas, "Informe," 20; Brünner, *Informe,* 36, 41-2.

[50] Bernasconi and Rojas, "Informe," 20.

[51] Bernasconi and Rojas, "Informe," 20-1; Vessuri, "The universities," 18.

[52] Bernasconi and Rojas, "Informe," 20.

Chileans were expelled from academic institutions during those years.[53] In addition to the massive dismissal of university faculty and students, a substantial number of professors fled the country during the post-coup period. This virtual expulsion from Chile gave rise to the so-called "Latin American academic Diaspora," a process that, in some cases, expelled majorities of researchers in whole areas of knowledge.[54] Although the academic disciplines most heavily affected by the military intervention were those in the field of social sciences such as sociology and political science,[55] researchers in the sciences were also impacted primarily due to the lack of economic and research opportunities under the Pinochet regime. For example, Saavedra, Cori and Anguita (1976) finds that, for three and a half years from 1974, Universidad de Chile's Department of Physical Sciences and Mathematics was losing full-time researchers at a rate of one per month.[56] In the field of theoretical physics, the exodus reached 65% of all researchers in the field between 1973 and 1988.[57]

With the transition from an authoritarian regime to democratic rule in 1990, institutional autonomy of higher education establishments was fully restored, cancelling all measures of governmental intervention and reinstating the right of faculty members to freely choose their authorities.[58] The evolution of Chile's higher education system reveals the effects that the authoritarian regime had on universities and research communities in the Southern Cone country. However, more than anything, the historical progression should bring to light how remarkable the development of Chilean astronomy has been. Despite the institutional impediments imposed on the academic community during the Pinochet era, Chile

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[53] Manuel Antonio Garretón and Hernán Pozo, *Las universidades chilenas y los derechos humanos* (Santiago de Chile: FLACSO, 1984), 14.

[54] Rodrigo Arocena and Judith Sutz, "Changing knowledge production and Latin American universities," *Research Policy* 30 (2001): 1224.

[55] Brünner, *Informe*, 44.

[56] Igor Saavedra, Osvaldo Cori, and Claudio Anguita, "La investigación básica," in *Las ciencias naturales en Chile: visión crítica y perspectivas*, ed. Osvaldo Cori (Santiago de Chile: CPU, 1976), 69.

[57] Brünner, *Informe*, 43-4; Vessuri, "The universities," 29.

[58] Brünner, *Informe*, 40.

has, in less than three decades' time, emerged as a major international actor in observational astronomy. It is, therefore, all the more pertinent to study how Chile has succeeded in restoring and boosting its science population, as well as how the country has built its "structurally achieved" system in the field of astronomy.

2. Linkages with International Institutions and Observatories

2.1 *Collaboration with International Institutions and Observatories*

Chilean universities launched astronomy departments and programs predominantly from the 1990's to promote astronomical research and foster education at both undergraduate and graduate levels. Not only have these universities set up new astronomy programs during the last three decades, they have also become progressively more involved in areas such as computing and instrumentation. Astronomy departments in large Chilean universities have begun to combine efforts with other science departments such as Electrical Engineering and Computer Sciences by establishing joint-research groups, laboratories and centers of excellence. Through these groups and centers, several of these universities have developed collaboration agreements with a number of universities and research institutes abroad that host some of the best astronomy programs in the United States, Canada, Europe, and, to a lesser extent, in Asia and Latin America.[59] Increasingly, Chilean institutions have also worked in partnership with international observatories to conduct joint research and develop new technologies and instrumentation for the telescopes. The following subsections provide an overview of the partnerships that have been established by three Chilean universities—Universidad de Chile, Pontificia Universidad Católica de Chile and Universidad de Concepción—with international institutions, research centers and observatories.

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[59] CONICYT, "Astronomy, Technology, Industry," 43-5.

2.1.1 Universidad de Chile

Partnerships with Universities and Research Centers Outside of Chile

Universidad de Chile has established agreements with the following North American institutions: Yale University, Princeton University, Massachusetts Institute of Technology, Cornell University, California Institute of Technology's Jet Propulsion Laboratory (JPL), Georgia Institute of Technology, Boston University, University of Michigan, University of Washington, Taylor University, Embry-Riddle Aeronautical University, SRI International and Herberzg Institute for Radio Astronomy (Canada). In Europe, Universidad de Chile has collaborated with University of Cologne (Germany), Group for Advanced Receiver Development (GARD) and Physical Electronic Laboratory (MC2) at Chalmers University (Sweden), Delft University of Technology (Netherlands), Institute of Electronic Materials Technology (Poland), Netherlands Institute for Space Research, Rutherford Appleton Laboratory (United Kingdom), University of Manchester (United Kingdom), Yebes Astronomy Center (Spain), and University of Napoli (Italy). The Chilean university has also established partnership with the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), which is based in Taiwan. These collaborations have been developed to foster academic and student exchange; organize international meetings and symposiums on emerging topics in astronomy; and to conduct joint-research for the construction of millimeter and submillimeter receiver components, site testing, and the development of specific parts for observatories.[60] Examples of the types of collaborations and their research objectives and outcomes are outlined below in Table 5.1.

A concrete example of such partnership involves the academic background of Dr. Ezequiel Treister, an alumni of Universidad de Chile who currently teaches at Pontificia Universidad Católica de Chile. After completing his undergraduate studies in Physics, he

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[60] Ibid.

Table 5.1. Partnerships developed by Universidad de Chile

Partner Institution	Type of Collaboration	Research Areas
Yale University (United States)	Joint program for graduate training and research	
Princeton University (United States)	Graduate training and research	
Cornell University (United States)	Joint research	
Boston University (United States)	Joint research	Modeling and simulation of unstable plasma at the auroral region
Taylor University (United States)	Joint research	Construction of a Langmuir Probe to be placed in the CubeSat under development by the group
Embry-Riddle Aeronautical University (United States)	Joint research	Modeling and simulation of unstable plasma at the auroral region
SRI International (United States)	Joint research	Search for Kangmuir harmonics signatures in incoherent Scatter Radar spectra at auroral region
University of Cologne (Germany)	Joint research	THz-spectroscopy, loaned 780mm dual-laser optics for LT-GaAs photomixer testing; optically pumped FIR-Ring laser for THz-detection device testing; general collaboration and support
Chalmers University (Sweden)	Training and consultation; access to lab facilities	Training and consultation for micro-fabrication of novel travelling-wave UTC photodiodes for terahertz generation
Delft University of Technology (Netherlands)	Joint research; access to lab facilities	Micro-fabrication of novel travelling-wave MIM-junctions for THz-generation
Institute of Electronic Materials Technology (Poland)	Joint research	Growth of specialized semiconductor wafers for micro-device fabrication at cleanroom facilities

Sources: CONICYT, “Astronomy, Technology, Industry: Roadmap for the Fostering of Technology Development and Innovation in the Field of Astronomy in Chile,” 2012; Universidad de Chile, “Department of Astronomy,” http://www.das.uchile.cl/web_en/index.html.

joined the Universidad de Chile-Yale joint program, where he spent a considerable amount of time in the United States to pursue his research. After completing two postdoctoral fellowships in international observatories, he returned to Chile to teach as a professor of astronomy.[61] Most professors and researchers currently residing at Universidad de Chile seem to share similar academic experiences as Dr. Treister. Dr. Monica Rubio of the Astronomy Department, for instance, received her PhD from University of Paris after finishing her undergraduate and master's coursework at Universidad de Chile.[62] As both Dr. Treister and Dr. Rubio claim, they pursued their education overseas primarily because there were no graduate programs in astronomy available at the time in Chile. Yet, observers of Chilean astronomy note that younger generations of astronomers today also actively go overseas to study, create networks and conduct research with international actors, despite the availability of postgraduate programs in astronomy in the country.[63] As these astronomers return to Chilean universities to teach, they impart knowledge to the new generation of local astronomers and contribute to the development of astronomical community in the Latin American country. Along with the partnerships that Universidad de Chile has established with a number of notable international institutions, the mechanism of Chilean astronomers studying abroad and returning to Chile with advanced astronomical knowledge has also been a significant factor to the development of Chilean astronomy.

Partnerships with International Observatories

A number of joint research activities have taken place between Universidad de Chile's Department of Astronomy and international observatories in the last few decades. One prominent example is the Calán/Tololo Supernova Survey, conducted as a collaboration

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[61] Treister, interview.
[62] Monica Rubio, interview by author, April 14, 2016.
[63] Satoko Takahashi, interview by author, April 11, 2016.

between Universidad de Chile and CTIO from 1989 to 1995. This survey paved the path for the discovery of the accelerated expansion of the Universe, and the teams involved in this discovery were awarded the Nobel Prize in Physics in 2011. More recently, Universidad de Chile launched the Millennium Nucleus for Protoplanetary Disk Research with ALMA, which aims to understand how planets form by utilizing the observatory's new telescopes.[64] Universidad de Chile has also been involved in APEX Telescope Large Area Survey of the Galaxy (ATLASGAL), which is an observing program with the LABOCA bolometer array at the Atacama Pathfinder Experiment telescope (APEX). This project was initiated in collaboration with the Max Planck Society—which includes Max-Planck-Institut für Radioastronomie (MPIfR) and Max-Planck-Institut für Astronomie (MPIA)—as well as the members of ESO.[65] The Chilean university has also joined forces with the U.S. National Radio Astronomy Observatory Technology Center for consultation support in technical questions on the photonic system of ALMA, as well as for support for research on risk mitigation and projects for the Atacama observatory.[66]

2.1.2 Pontificia Universidad Católica de Chile

Partnerships with Universities and Research Centers Outside of Chile

Pontificia Universidad Católica has established academic exchange programs and designed and constructed instrument parts for telescopes in collaboration with the Astronomical Institute at the Ruhr University Bochum (Germany), University of Durham (United Kingdom), National Institute for Astrophysics (Italy), Harvard Smithsonian Center for Astrophysics (United States), and with the universities involved in the Atacama

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[64] Universidad de Chile, "Department of Astronomy," http://www.das.uchile.cl/web_en/index.html.

[65] ATLASGAL, "The APEX Telescope Large Area Survey of the Galaxy," http://www3.mpifr-bonn.mpg.de/div/atlasgal/index.html.

[66] CONICYT, "Astronomy, Technology, Industry."

Cosmology Telescope (ACT) project.[67] Examples of the types of collaborations and their research objectives and outcomes are summarized below in Table 5.2. Similar to the situation in Universidad de Chile, the majority of Chilean professors at Católica's Institute for Astrophysics have studied overseas. Dr. Gaspar Galaz, the Director of the Institute, received his PhD from University of Paris and completed his postdoctoral fellowship at the Carnegie Institution before returning to Chile to teach at Católica.[68] This constant flow of Chilean researchers moving abroad and coming back to Chile has, as previously highlighted, helped to create a momentum in developing Católica's astronomy agenda.

Table 5.2. Partnerships developed by Pontificia Universidad Católica

Partner Institution	Type of Collaboration	Research Areas
University of Durham (United Kingdom)	Joint research; academic exchange	Tomographic reconstruction for multi-object adaptive optics; pre-conceptual design of an instrument for ESO; new instruments for turbulence profiling for ELT scales
Harvard Smithsonian Center for Astrophysics (United States)	Partnership	Design and construction of the two cryogenic focal planes for G-Clef instrument and the Exposure Time Calculator
National Institute for Astrophysics (Italy)	Partnership	Phase A study of SIMPLE, a high resolution near IR-echelle spectrograph for the E-ELT

Sources: CONICYT, "Astronomy, Technology, Industry."

Although smaller in scale compared to other collaborations, Universidad Católica, along with Universidad de Chile, hold an international forum with the University of Tokyo once every two years to promote academic and student exchange and to share the latest research activities in various academic disciplines. In 2013 in Santiago de Chile, for instance,

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[67] Ibid.

[68] Gaspar Galaz, interview by author, April 12, 2016.

professors and researchers of the universities discussed the advancements in astronomical technology and instrumentation, as well as the progress of Chile-Japan astronomical collaborations in the Atacama Desert.[69]

Partnerships with International Observatories

Like Universidad de Chile, Universidad Católica has also established partnerships with international observatories and projects. With Gemini Observatory, for example, Católica initiated a joint-research program to develop the multi-conjugate adaptive optics instrument.[70] The Chilean university also collaborated with American universities involved in the ACT project—specifically with Princeton University, Rutgers University and Pennsylvania State University—for the development of submillimeter telescopes.[71] Furthermore, following ESO's initiative to build the Multi-Object Optical and Near-infrared Spectrograph (MOONS) for its Very Large Telescope (VLT), Católica's Center for Astro-Engineering (AIUC) joined the international consortium in 2004 to develop the wide-field spectrometer.[72] The Center has also become a member of the consortium to design the Extremely Large Telescope (ELT). Another recent example is the TAO-AIUC high Resolution Y band Spectrograph (TARdYS), which is one of the most advanced and ambitious projects developed in AIUC in the line of high-resolution spectroscopy. TARdYS involves an agreement between TAO and Católica, which aims to foster collaboration between the two institutions in developing the 6.5 m large-aperture telescope to be positioned at the highest point of Cerro Chajnantor in the Antofagasta Region.[73]

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[69] Kentaro Motohara, interview by author, April 12, 2016.

[70] Ibid.

[71] Princeton University, "The Atacama Cosmology Telescope." https://act.princeton.edu/.

[72] Pontificia Universidad Católica de Chile, "Centro Astro-Ingeniería," http://www.aiuc.puc.cl/.

[73] CONICYT, "Astronomy, Technology, Industry," 56,

2.1.3 Universidad de Concepción

Partnerships with Universities and Research Centers Outside of Chile

Though to a lesser extent when compared to the two previous institutions, Universidad de Concepción has also cultivated academic and student exchange programs and conducted joint research with the Electrical and Computer Engineering Department of the University of New Mexico (United States), the Astronomy Department at the California Institute of Technology, the Department of Aerospace and Mechanical Engineering at the University of Liège (Belgium), as well as with the Center for Telecommunications Studies at the Pontifícia Universidade Católica do Rio de Janeiro (Brazil).[74]

Partnerships with International Observatories

Recently, the Radio Astronomy Laboratory at Concepción has established links with the Haystack Observatory of the Massachusetts Institute of Technology to participate in the NSF1 Major Research Initiative, consisting of adding a VLBI Backend to the ALMA observatory and allowing integration in a worldwide very long-baseline interferometer. This effort intends to achieve an angular resolution that is able to map the surrounding physical conditions of very compact objects, such as the Black Hole in the center of the Milky Way Galaxy.[75]

2.2 *Knowledge Transfer: From Collaborations to Research Initiatives by Chilean Institutions*

Each of the three universities examined—Universidad de Chile, Pontificia Universidad Católica de Chile and Universidad de Concepción—have established partnerships with a number of foreign universities and research centers, generally based in Europe and the United States. These partnerships have taken a variety of forms: graduate training, joint research,

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[74] CONICYT, “Astronomy, Technology, Industry”; Pontificia Universidad Católica de Chile, “Centro Astro-Ingeniería.”

[75] CONICYT, “Astronomy, Technology, Industry,” 15-6.

training and consultation, to name a few. Although these joint programs should certainly be noted, the presence of these collaborations alone should not be interpreted as an indicator of successful knowledge transfer. In order for knowledge to be transferred, scientific and technological knowhow needs to be captured and applied to the circumstances in which the universities are located. It is necessary, thus, to verify whether these collaborations have enabled knowledge and technological knowhow to be transferred from international organizations to the local astronomical community in Chile. Furthermore, it is essential to determine whether the partnerships between Chilean and international institutions and subsequent knowledge transfers have permitted the formation of a more institutionalized community of Chilean astronomers. This section will first investigate how each of the three universities utilized knowledge obtained from the joint collaborations to initiate their own research centers and projects independent of foreign institutions. It will then assess how Chilean universities have strengthened links with one other to develop further Chile's capacity for astronomical research.

2.2.1 Research Initiatives by Chilean Institutions

i. Universidad de Chile

Since its founding in 2004, Universidad de Chile's Millimeter-Wave Laboratory (ML) has contributed to the endogenous development of astronomical instruments and technologies. Run by the Departments of Astronomy and Electrical Engineering and the Faculty of Physical and Mathematical Sciences, the Laboratory is located at the National Astronomical Observatory on Cerro Calán. The ML designs, builds and tests state-of-the-art receivers, front-end components and digital spectrometers to be used in research related to radio astronomy. Within the last few years, the Laboratory has succeeded in developing a prototype receiver for ALMA.[76] In 2008, furthermore, the three aforementioned departments—the Department of Electrical Engineering, Faculty of Physical and Mathematical Sciences and the Astronomy Department—established the Radio Astronomical Instrumentation Group (RAIG), which consists of the above-mentioned Millimeter-Wave Laboratory, Photonics Laboratory, and the Space and Planetary Exploration Laboratory (SPEL).[77] The Photonics Laboratory at the Department of Electrical Engineering, founded in 2008, has been engaged in the design and fabrication of photonic instruments to be applied in the field of astrophysics. For example, the Laboratory has been involved in the technological development of the photonics system and devices, as well as the fabrication of terahertz radio-frequency receivers, which entail specialized imaging and spectrograph systems.[78] SPEL, since its conception in 2011, has served as a hub for researchers, engineers, and students to collaborate on space physics and space instrumentation. A notable example of its work is the Satellite of the University of Chile for Aerospace Investigation (SUCHAI), which was the first Chilean CubeSat—a miniaturized satellite for astronomical research—developed by students, engineers and professors associated with SPEL.[79]

ii. Pontificia Universidad Católica de Chile

Run jointly by the Departments of Astronomy and Astrophysics, Electrical Engineering, Computer Science, and Physics, the Center for Astro-Engineering (AIUC) was founded in 2009 to serve as a link between scientific research and technological and computational

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[76] CONICYT, “Astronomy, Technology, Industry,” 15-6; Universidad de Chile, “Department of Astronomy”; Universidad de Chile, “Millimeter-wave Laboratory,” http://www.das.uchile.cl/lab_mwl/index.html.

[77] Universidad de Chile, “Radio Astronomical Instrumentation Group,” http://www.raig.uchile.cl/home.

[78] Universidad de Chile, “Laboratorio de Fotónica,” http://ingenieria.uchile.cl/investigacion/presentacion/laboratorios/90806/laboratorio-de-fotonica.

[79] Universidad de Chile, “Space and Planetary Exploration Laboratory,” http://spel.ing.uchile.cl/.

developments in the field of astronomy. This Center is involved in the development of high-resolution optical spectrographs; adaptive optics (i.e. Wide-field, beam-shaping, Cn2 characterization); design and fabrication of cryogenic cameras, scientific CCDs and NIR detectors; fiber optics; astronomical site testing; evaluation of telescope performance for the ACT project; high-performance computing, numerical simulation and database management; and planet finding. AIUC developed the Fiber Dual Echelle Optical Spectrograph (FIDEOS)—a high-resolution spectrograph that provides high stability for radial velocity measurement—which was designed and constructed by Chilean scientists, graduate students and engineers. Though relatively small in scale, this indigenous instrument represents an important step towards the participation of AIUC in the design and fabrication of larger instruments.[80]

iii. Universidad de Concepción

Since its establishment in 2009, Universidad de Concepción's Radio Astronomy Laboratory has been engaged in projects related to instrumentation, such as the millimeter-VLBI; refurbishment, site testing and characterization of radiometers; and the development of radiometers used for weather forecasting and data calibration. A notable example is the development of digital-backend profiling radiometers used to monitor the amount of water vapor in the atmospheric column at observatory sites. Accurate measurements of atmospheric humidity are essential to observational astronomy: because some astronomical spectral bands are sensitive to absorption by water vapor in the atmosphere, these radiometers are extremely useful in identifying and selecting suitable places for the construction of radio- and millimeter-wavelength observatories. The Center for Optics and Photonics (CEFOP),

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[80] CONICYT, "Astronomy, Technology, Industry," 15-6; Centro de Astrofísica y Tecnologías Afines, http://www.cata.cl/; Pontificia Universidad Católica de Chile, "Centro Astro-Ingeniería."

moreover, has been involved in the development of infrared imaging since its establishment in 2010. Currently, the Center is involved in the development of software and hardware design and implementation of hyperspectral imaging; development of optical sensors; eVLBI data transferring; and optical interferometry, including long-distance microwave-antenna design.[81]

2.2.2 Collaborations between Chilean Institutions

As the previous section illustrated, Chilean astronomy has seen an expansion of research centers, astrophysics laboratories and projects established by the three large universities. Although it was previously considered “strange” to collaborate with researchers from different institutions,[82] these universities have come to foster and strengthen links with one another to develop further Chile’s institutional capacity for astronomical research. The Director of Universidad Católica’s Institute of Astrophysics, for example, visits Universidad de Chile’s Director at least once or twice a month to discuss potential research projects; Católica’s professor is also a member of an astronomical research group at Universidad de Chile.[83] Dr. Christian Moni of Universidad Católica del Norte also utilizes his connections from his previous post at Universidad de Concepción and continues to conduct joint-research projects with his former colleagues.[84] At a more institutional level, three prominent inter-university partnerships have recently been established: the Center for Excellence in Astrophysics and Associated Technologies (CATA), Millennium Center for Supernova Science (MCSS), and the collaboration between the National Laboratory of High-Performance Computing (NLHPC) and Center for Mathematical Modeling (CMM).

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[81] CONICYT, “Astronomy, Technology, Industry,” 15-6.

[82] Galaz, interview.

[83] Ibid.

[84] Ohnaka, interview.

i. Center for Excellence in Astrophysics and Associated Technologies (CATA)

Since its founding in April 2008, CATA has been the largest Chilean project for research and development of astronomical technologies. A project approved under a 10-year funding scheme of the National Commission for Scientific and Technological Research (CONICYT), the Center brings together a total of 35 researchers and 50 postdoctoral fellows, along with dozens of graduate students at master's and doctoral levels from Universidad de Chile, Pontificia Universidad Católica and Universidad de Concepción. The Center's mission is to cultivate greater research capacity and to develop new technologies in the field of astronomy; contribute to the training of researchers involved in such activities, particularly at postgraduate levels; establish collaborative networks both domestically and internationally; and to foster greater community involvement in conducting research. Six projects under CATA are dedicated to the investigation of the following topics: the birth and evolution in the structures of the universe; stellar population of the universe; the extragalactic distance scale; star formation; extrasolar planets and brown dwarfs; and supernovae and dark matter. The Center also focuses on the development of technology, namely in bolstering activities for astronomical instrumentation. Members of CATA, for instance, have been engaged in the development of prototype receivers for ALMA, as well as the production of receivers for other observatories based in Chile.[85]

ii. Millennium Center for Supernova Science (MCSS)

Founded in 2008 by three astronomers—two from Universidad de Chile and one from Pontificia Universidad Católica—MCSS aims to cultivate an environment that supports supernovae-related research in the Southern Cone country. The primary objectives of the

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[85] Centro de Astrofísica y Tecnologías Afines; Universidad de Chile, "Department of Astronomy"; Rubio, interview.

Center are to conduct astronomical research that will place Chile at the scientific frontier in the field of supernovae studies; to stimulate interaction and scientific communication between researchers and students of Chilean universities; to sponsor multi-institutional operations and collaborations in the field of supernovae studies; to contribute to the formation of new generations of Chilean scientists and further the development of theoretical astrophysics in Chile; and to bridge the gap between the astronomical community and the Chilean society. Soon after the project was initiated, a number of postdoctoral researchers, graduate students and astronomers from both universities joined the Millennium Center. Due to increasing interest from the astronomical community, MC has grown substantially since 2008. As of 2016, it is composed of 20 members from Universidad de Chile, four from Universidad Católica and two from Universidad Nacional Andrés Bello.[86]

iii. Partnership between the National Laboratory of High-Performance Computing (NLHPC) and Center for Mathematical Modeling (CMM)

Another important collaboration that has been taking place in Chile entails the partnership between NLHPC and CMM. This collaboration has also welcomed the participation of Pontificia Universidad Católica, Universidad de Santiago de Chile, Universidad Técnica Federico Santa María, Universidad de Talca, Universidad de La Frontera (UFRO) and Universidad Católica del Norte. This NLHPC-CMM partnership has the potential to play a key role in managing, processing, and analyzing astronomical data obtained from observations conducted at the Large Synoptic Survey Telescope (LSST). Because the partnership offers the necessary infrastructure and expertise to provide computing power for the analysis of LSST data, the collaboration will enable LSST to detect an

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[86] Millennium Center for Supernova Science, http://www.mcss.cl/index.php?lang=en; Universidad de Chile, “Department of Astronomy”

unprecedented volume of transient events per night including supernovae, new variable stars, asteroids and comets.[87]

3. Recapping the Knowledge Transfer Mechanism: Chile's Astronomy Collaborations

Chilean universities with the largest astronomy programs—Universidad de Chile, Pontificia Universidad Católica and Universidad de Concepción—have collaborated with numerous foreign universities, research institutions and international observatories across the world to encourage academic exchanges, joint-research programs, and overall astronomical training and consultation. In addition, the movement of qualified astronomers going abroad and returning back to Chile has enabled the local astronomical community to expand its reservoir of knowledge in the field of astrophysics. As a result of these processes, Chile's astronomical society has not only captured a large volume of knowledge, but has also gained practical experience in collaborating on research and technological projects with renowned institutions from across the globe.

With the knowledge and experience acquired in conducting world-class research and initiating technological projects, astronomers from the three Chilean universities have begun to utilize the transferred knowledge to establish new laboratories and research centers to, for example, construct state-of-the-art receivers and to design high-resolution spectrographs for international observatories based in Chile. These universities, in other words, successfully applied the knowledge acquired from the aforementioned partnerships and launched their own projects that cultivate endogenous astronomical research. Furthermore, Chilean astronomy has gradually departed from a more individualized approach to research—where individual astronomers or university departments collaborate with one another when the need to conduct specific projects arises—to a more institutionalized approach. This is reflected in the inter-

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[87] CONICYT, "Astronomy, Technology, Industry," 17.

university partnerships that have recently been founded in Chile: CATA, MCSS, and the collaboration between NLHPC and CMM. By establishing a collaborative mechanism that enables astronomers to research and interact with one another, the Chilean astronomical community can distribute knowledge more effectively, as well as create greater partnership opportunities for astronomers to conduct more advanced and large-scale research projects.

II. Convergence of Implicit and Explicit Astronomy Policies

As Herrera (1973) maintains, science policy is a product of interplay between explicit and implicit policies. The content of explicit policy—which is the apparent objectives of the national science system—must coincide with the scientific and technological demands and “implicit” aspirations of the population. Although divergence between explicit and implicit policies has been a more common reality than policy convergence in Latin America, this paper argues how consensus between the two policies has been achieved in Chilean astronomy. This section is organized as follows. It will first sketch the “implicit” scientific demands of Chilean astronomers, and it will then analyze how these local aspirations have been embraced and promoted by the explicit, state-led policies of the Chilean government.

1. Implicit Policy: Reaching for the Stars

Since the establishment of Cerro Tololo, Las Campanas and La Silla Observatories in the 1960s, a number of world-class observatories and telescopes have been constructed in the northern region of Chile—and many more are currently under construction. Echoing this development of observatories, the Latin American country has seen a rapid expansion of astronomy programs being offered at Chilean universities since the 1990s; an inflationary growth of professional astronomers; increase in the number of academic papers published by these astronomers; and, as the previous section highlighted, a rise in domestic and international collaborations for astronomical research. Moreover, in May 2000, the Union of Professional Astronomers (SOCHIAS) was established with the primary aims of developing and promoting the field of study and representing the community of professional astronomers in Chile.[88]

These recent developments in Chile also reflect the scientific and technological aspirations of local astronomers. With its dark skies and geographical features, Chile has been blessed with a "natural laboratory" for astronomical research[89] that has attracted the world's most ambitious observatories and projects. There is a general consensus among Chilean astronomers that these observatories function as "a testbed for some of the newest and state-of-the-art technologies in the world,"[90] and Chile's science community can benefit substantially from these projects. By taking advantage of its high-quality natural laboratory and the presence of international observatories and research communities, Chilean researchers believe that "astronomy has the potential to be the leading science in Chile, in South America—even in the world."[91] Astronomy, in other words, presents possibilities for Chile to demonstrate its scientific and technological capability to the global community. Moreover, astronomy can act as a "pilot test" for Chile[92] so that other fields of science can also develop and contribute to the formation of its knowledge-based economy.

As the developments in Chilean astronomy and the voices of local astronomers reveal, the science community in Chile aspired to transform astronomy into the leading field of study. The scientific and technological aspiration of the population, therefore, was to develop Chilean astronomy by utilizing its natural laboratory and the scientific influx from international observatories. The next section examines how this implicit policy has converged

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[88] Treister, interview.
[89] Rubio, interview.
[90] Treister, interview.
[91] Gómez, interview.
[92] Rubio, interview.

with the government's explicit policy to cultivate Chile's astronomical community.

2. Explicit Policy: Government Support for Astronomy

Since the first telescopes were installed in Cerro Tololo, Las Campanas and La Silla in the 1960s, Chilean governments have reliably and continuously supported the discipline of astronomy. Despite the dramatic changes in governance throughout Chile's political history—from Pinochet's authoritarian military regime in the 1970s to the return of democracy in 1990—astronomers, during the entire progression, "were respected by the government," and support from the Chilean government for international projects never faltered.[93] As a Chilean astronomer puts it aptly, "[t]he political conditions in Chile can be one thing, and the atmosphere and environment for external guests is completely different."[94] The Chilean government, therefore, has long supported the astronomical community by providing an institutional framework that has allowed leading international organizations to establish themselves in Chile for the development and operation of astronomical observatories. Not only has the government facilitated the process for international organizations to initiate and maintain their operations in Chile, it has also supported local astronomers to nurture their astronomical capabilities. This section will highlight four "explicit" policy packages that the government of Chile has implemented, which demonstrate convergence with the implicit aspirations of local astronomers. Analysis of the first two policies—the provision of diplomatic and tax-free status for observatories and access to telescope time—will be followed by the examination of CONICYT's Astronomy Program. The section will then delve into the measures taken by the government to reduce the effects of light pollution in the northern regions of Chile.

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[93] Treister, interview.

[94] Gómez, interview.

2.1 *Diplomatic Status and Tax Exemptions*

Since the 1960s, the government of Chile facilitated the construction of international observatories by granting them diplomatic and tax-free statuses. This condition was first enforced in November 1963, when the Chilean government signed an international treaty with ESO, promulgated by means of supreme decree N° 18 of January 4, 1964 of the Ministry of Foreign Affairs. This treaty granted ESO the same immunities, prerogatives and facilities as those granted to diplomats and international organizations. Two years later in October 1965, the government once again issued Decree N° 2.940 of the Ministry of Finance, specifying the tax exemptions that would be granted to the European observatory. This decree permits exemption from income tax and land tax for the real-estate property of ESO; exemption from tax on purchase and sale of materials; exemption from tax on the annual transactions volume for rendering services to ESO; and exemption from tax on stamps, seals and officially-stamped papers for contracts signed for the projected work. The same diplomatic and tax-free statuses were granted to the American observatories in September 1969, in virtue of Law N° 15.182. Today, all of the observatories based in Chile are granted diplomatic status and exemption from the 19% value-added tax.[95] Needless to say, this legal framework has made northern Chile a more attractive and cost-effective site for constructing observatories in comparison to, for example, Hawaii and the Canary Islands. These decrees highlight the Chilean government's enduring support for low-cost operation of research activities, as well as its commitment to solidify the country's prestige in international astronomy—precisely the kind of support that mirrors the aspirations of local astronomers.

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[95] AURA, "A Charter for the Operation and Management of AURA's Observatory in Chile," September 2009, http://www.aura-astronomy.org/about/policies/Section%20A/18)%20A-XVIII%20A%20Charter%20for%20the%20Operation%20and%20Management%20of%20AURA's%20Observatory%20in%20Chile.pdf; Barandiaran, "Reaching for the Stars," 152-3; Leighton, "Chile"; James Mullin et al., *Science, Technology, and Innovation in Chile* (Ottawa: International Development Research Centre, 2000), 101.

2.2 *Chilean Access to Telescope Time*

Until the late 1990s, access to international observatories were largely unavailable to Chilean astronomers. Yet, the situation changed after 1997, following a dispute over the construction of Paranal Observatory. This dispute began in 1988, when ESO received 725 km^2 of land near the mountain of Paranal—located in the northern part of the Atacama Desert—for the construction of the Very Large Telescope (VLT). The military regime under Pinochet expropriated this land from a family in 1977 and in 1986 declared it a "science reserve for mining purposes," effectively forbidding mining activities without presidential approval. After ESO claimed the land in 1993, the family that originally owned the land took ESO and the Chilean government to court, claiming that the land had been illegally expropriated. Although the case was eventually dismissed, the dispute sparked a broader reexamination of international observatories in Chile: lawmakers, along with the astronomical community led by Universidad de Chile and Universidad Católica, decided to step in and put pressure on the government to negotiate improved conditions for local astronomers and to place Chilean scientists on a more equal footing with foreign researchers. As a result, the government passed Decree 1766 in May 1997, which ensured that 10% of observation time for all telescopes and observatories will be granted to projects proposed by astronomers at Chilean institutions.[96] This means that researchers affiliated with Chilean universities and institutions are eligible to apply for the 10% telescope time, regardless of their nationality. These astronomers, however, must be enrolled in Chilean institutions during the time of the requested observations and need to maintain continuous residence in Chile for at least nine months. For postdoctoral students applying for the 10% timeslot, they need to incorporate at least one faculty member in their projects when writing proposals.[97]

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[96] Barandiaran, "Reaching for the Stars," 152; Gómez, interview.

[97] Jorge E. Allende, *Análisis y proyecciones de la ciencia chilena 2005* (Santiago de Chile: Academia Chilena de Ciencias, 2005), 242; Barandiaran, "Reaching for the Stars," 141-2; Universidad de Chile, "Department of Astronomy"; Ohnaka, interview.

This 10% timeslot has had a considerable impact on the development of Chilean astronomy. Firstly, it enabled Chilean astronomers to get their foot into the world of astronomical research and run projects alongside researchers from other parts of the world. Prior to the allocation of Chilean observation time, the small community of local astronomers needed to compete with a much larger group of researchers from more established research institutes across the world to use the telescopes; yet, because the 10% slot is now divided amongst projects conducted by researchers from Chilean institutions, there is less competition—and more opportunities—for undertaking research projects. CONICYT, for instance, found that the pressure factor on a telescope—which is defined as the ratio of the number of requested nights to the number of available nights[98]—in Gemini South from 2008 to 2011 was, on average, 1.97.[99] This means that astronomers from Chilean institutions request only twice the available nights to conduct observations at Gemini. On the other hand, the average pressure factor outside of the Chilean timeslot fluctuates around 5, indicating that the number of requested nights are five times of those that can be allocated.[100] Although higher pressure factors are desirable for healthy competition within the astronomical community, the 10% timeslot has enabled Chilean astronomers to take advantage of the world-class facilities and to become more involved in astronomical research.

The increased availability of observation time since 1997 also opened the door to astronomical research to new astronomers which, consequently, has led to the expansion of the local astronomical community. As a professor from Andrés Bello claims, “[f]or a very long time, astronomy was dominated by Universidad de Chile and Universidad Católica; but the situation changed [after the 10% regulation], and a new group of smaller universities

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[98] C. Jaschek and C. Sterken, *Coordination of Observational Projects in Astronomy* (Cambridge: University Press, 1988), 213.

[99] CONICYT, “Tiempo de Observación Telescopio: GEMINI-SUR (2008-2011),” http://www.conicyt.cl/astronomia/files/2012/08/Tiempo-de-Observaci%C3%B3n-Telescopio-GEMINI-SUR-2008-2011.pdf.

[100] Allende, *Análisis y proyecciones*, 242.

began to emerge in, for example, Concepción and La Serena." Furthermore, the 10% telescope time became "a tremendous channel for collecting data." Although the pressure factor within the Chilean timeslot is still small, it has become increasingly competitive to have the proposals accepted, especially because Chilean postdoctoral fellows that receive their degrees overseas and return to Chile are becoming ever more skilled and talented. For example, the number of submitted proposals have multiplied over the last decade, and close to 200 proposals are currently submitted twice a year to the Chilean Telescope Allocation Committee (CNTAC). The new generation of astronomers, moreover, bring their own collaborators and groups from the United States, Europe and Japan, which have stimulated research and contributed to the development of the local astronomical community.[101]

2.3 *CONICYT's Astronomy Program*

In 2006, CONICYT founded the Astronomy Program with the objectives of positioning astronomy as a strategic area for scientific development in Chile and to transform the Southern Cone country into a world power in astronomy. As the only thematic discipline to have its own program in CONICYT, the Astronomy Program promotes scientific and technological cooperation and attracts new projects and investments in astronomy via national and international alliances. Some of the main achievements of this program include managing the Chilean observation time and, as will be explored more in depth below, awarding of funding to projects proposed by Chilean institutions, signing of the Scientific Cooperation Agreement in Astronomy with the Chinese Academy of Sciences (CAS) and constructing the Atacama Astronomy Park.[102] Yet, before enquiring into these achievements, the backdrop to the creation of the Program should be noted. As discussed previously, there was a rapid

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[101] Gómez, interview; Universidad de Chile, "Department of Astronomy."

[102] CONICYT, "Astronomy, Technology, Industry."

expansion of astronomy programs across Chile in the 1990s. Reflecting this development, there was a growing consensus among local astronomers that an official astronomical society that oversees the development and establishes a clear agenda of strategies and priorities was necessary. Also during this time, the former President of CONICYT—Dr. Vivian Heyl, who came into office in 2006 during President Michelle Bachelet’s first administration—discovered that the country’s astronomical community was administratively dependent on CONICYT. Yet, Dr. Heyl did not have a background in astronomy and, therefore, needed to create a division or program that would be responsible for the operation of astronomical activities. Dr. Monica Rubio of Universidad de Chile was appointed as the Director of CONICYT’s Astronomy Program in 2007, and she served as the program head for seven years until 2014.[103]

i. Funding for Astronomical Research

As briefly mentioned above, one of the main functions of the Astronomy Program is to award researchers with grants for their projects. This is an important task, considering how universities and research centers across all academic disciplines in Chile rely heavily on public funding. In astronomy, specifically, at least 50% of project funding comes from public sources. Funding for astronomy-related projects are provided with the aim of fostering highly-specialized technical groups for the development of astronomical instrumentation; forming research groups and developing new tools; for conceptual development and prototyping of instruments; and developing complex computer codes for data analysis and to support astronomical operations at international observatories. Funding for these projects primarily comes from CONICYT which, operating under the Ministry of Education, promotes the formation of advanced human capital and research capacity in science and technology. Key

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[103] Rubio, interview.

programs under CONICYT include the National Fund for Science and Technological Development (FONDECYT), which functions as the main public body for supporting individual research in Chile; the Fund for Financing Research Centers of Excellence (FONDAP), a program that sponsors collaborations between research institutions, companies and other entities with the objectives of advancing applied research and promoting projects to develop new technologies; the Associative Research Program (PIA), which seeks to create new science groups and research centers by encouraging collaboration amongst national and international actors; and the Astronomy Program.[104] The Astronomy Program has also secured funding for astronomical projects from international observatories, such as the GEMINI-CONICYT and ALMA-CONICYT grants, which aim to foster the development of astronomical instrumentation; formation of research groups and development of tools for accurate forecasting of turbulence and water vapor at astronomical sites; conceptual development and prototyping of instruments for accurate monitoring of atmospheric conditions at observatory sites; and the advancement in complex computer codes to support astronomical operations and data analysis at leading observatories in Chile.[105]

The breakdown of funding for astronomical projects is presented below in Table 5.3. Although there was drop in funding between 2006 and 2007 and again from 2008 to 2009, there is a general upward trend in funding for astronomical projects. Between 2006 and 2011, funding for Chilean astronomy increased from approximately US$2 million to US$6.8 million.

ii. Chile-China Collaboration

Following the agreement between the government of Chile and CAS in 2012, the Chinese Academy of Sciences South America Center for Astronomy (CASSACA) was established in

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[104] CONICYT, "Science, Technology and Innovation for the Development of Chile," 2011: 12-20, 50; CNIC, "Evaluation Report of National Innovation Strategy for Competitiveness, Chile," *International Evaluation Panel* (2010): 14; World Bank, *Chile: Toward a Cohesive and Well Governed National Innovation System* (Washington, D.C.: World Bank, 2008), 42.

[105] CONICYT, "Science, Technology and Innovation," 12.

Table 5.3. Astronomy funding (in thousand USD), 2006-2011

	2006	2007	2008	2009	2010	2011
CONICYT	2,027	1,811	4,720	4,216	5,384	5,693
FONDECYT	378	461	746	909	1,112	1,430
FONDAP	1,132	1,195	1,195	1,114	1,223	1,259
PIA	-	-	1,893	1,144	1,646	1,841
Astronomy Program	517	155	886	1,048	1,402	1,163
ALMA Fund	517	32	545	687	929	536
ALMA Postdoc	-	-	-	-	-	60
GEMINI Fund	-	118	305	328	436	528
GEMINI Postdoc	-	6	35	34	37	39
Millennium Science Initiative (ICM)	-	-	374	459	397	1,068
Total	2,027	1,811	5,094	4,675	5,781	6,760

Source: CONICYT, “Astronomy, Technology, Industry.”

2013, which aims to serve as a “bridge between astronomical communities of China and Latin America.” The Center promotes academic exchanges and collaborations in both scientific research and instrument-building, bolsters communication and cooperation with international observatories in Chile, and prepares for future Chinese observational establishments in the Southern Sky. The idea of establishing an astronomical center in Chile was first proposed by Chinese astronomers as a prelude to building a full-scale observatory; it then caught the attention of governments on both sides and led to its realization in 2013. Under the CASSACA framework, Chilean researchers collaborate with Chinese astronomers as faculty members and postdoctoral fellows and also engage themselves in the development of specialized telescopic instruments.[106] This scientific cooperation agreement with CASSACA reflects the Chilean government’s aspiration to strengthen the capacity of its astronomical community by expanding research and collaboration opportunities with emerging members of astronomy, as well to create more opportunities and paths for Chilean astronomers.

iii. Atacama Astronomical Park

A major initiative undertaken by CONICYT’s Astronomy Program has been the

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[106] Zhong Wang, interview by author.

development of the Atacama Astronomical Park, a 36,347-hectare scientific reserve located in the Atacama Desert. The idea originated in 2002 with the goal of facilitating the installation of smaller-scale astronomical projects in the areas surrounding ALMA and attracting future telescopes from the United States, Brazil, China, South Korea and Thailand.[107] The Astronomical Park is an ideal solution for small- and medium-size astronomical projects of under US$300 million, which are often operated by national or inter-university consortiums. Prior to the construction of the Park, these small-scale projects needed to complete and submit a large volume of paperwork so they can operate in the northern parts of Chile. For example, Johns Hopkins' Cosmology Large Angular Scale Surveyor (CLASS)—one of the five projects that are currently operating at the Astronomical Park—needed to negotiate contracts with both CONICYT and the ministry that manages the land where the observatories were located before receiving permits for its operation. Yet, with the establishment of the Astronomical Park, the ministry that is responsible for the land gave the right to control the partial site to CONICYT. Because these observational projects now only need to go through CONICYT to initiate their activities in Chile, the Astronomical Park minimized the bureaucratic steps to be completed.[108] The five astronomical projects that are currently in operation at the Park include CLASS, Berkeley's PolarBear, the Atacama Cosmology Telescope (ACT) Group, the Tokyo Atacama Observatory (TAO) and the Cornell Caltech Atacama Telescope (CCAT).[109] More information on each of these projects are provided in Appendix B.

Projects such as CLASS, ACT and TAO represent a great opportunity for astronomers and engineers in Chile to participate in research and technological development of instrumentation needed for these telescopes. It should also be noted that, like in other larger observatories, the 10% observation-time still applies to these small- and medium-sized

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[107] Catanzaro, "CHILE: Upward trajectory," 204-5.

[108] Chuck Bennet, interview by author, April 13, 2016.

[109] CONICYT, "Astronomy Program," http://www.conicyt.cl/astronomia/astronomy-program/.

projects operating at the Astronomical Park. Moreover, during the construction and initial operation stages, the projects are required to hire local employees from the region, which has contributed to the formation of Chilean technical personnel.[110]

2.4 *Regulations for Light Pollution*

Since the 19th century, the dark, clear skies of the Atacama Desert attracted astronomical observatories and renowned astronomers from across the globe. For a country like Chile—which is rapidly becoming the world's capital for observational astronomy—the issue of maintaining these dark skies and reducing the risks of light pollution is of great importance. Yet, astronomers that have worked in Chile claim that light pollution has increased sharply in the northern regions of Chile as mining cities swelled and tourist numbers began to multiply. Just over 100 km southwest of the Giant Magellan Telescope (GMT), the populations of Coquimbo and La Serena ballooned by almost 70% from 1992 to 2012, which have ushered in new buildings and facilities that excessively send artificial light into the atmosphere and reduce the visibility of the natural sky. Astronomers at Gemini Observatory, located approximately 60 km southeast of Coquimbo and La Serena, also state that light pollution has already had a measurable effect on the quality of astronomical observations.[111] However, in order to continue to attract international astronomical projects to Chile, the government has implemented a series of regulations intended to control and prevent light pollution and to preserve the photometric quality of the night sky in the northern regions. The following subsections outline these environmental norms or, more specifically, explicit

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[110] Ibid.

[111] Pablo Miranda Daud, "Discurso Del Representante de CONAMA," in *Light Pollution: The Global View*, ed. Hugo E. Schwarz (Berlin: Kluwer Academic Publishers, 2003), xviii; Pedro A. Sanhueza and Marianela P. Santander, "Protecting the Night Sky of Northern Chile: An Environmental and Cultural Heritage," in *Light Pollution: The Global View*, ed. Hugo E. Schwarz (Berlin: Kluwer Academic Publishers, 2003), 72; Gram Slattery, "In Chile, world's astronomy hub. Scientists fear loss of dark skies," *Reuters*, December 16, 2015, http://www.reuters.com/article/us-chile-astronomy-idUSKBN0TX27B20151216.

state-led policies that have aimed to maintain Chile's presence in international astronomy.

i. DS686: Law for Regulating Light Pollution

Facing the need to control light pollution particularly in the regions where astronomical activities take place, the Chilean government, together with other public and private institutions, instigated a series of measures. To regulate *contaminación lumínica*, or light pollution, the Ministry of the Environment (CONAMA) implemented in August 1999 the Supreme Decree #686/98, more commonly known as DS686. This law—*Ley de protección de contaminación lumínica*, which directly translates to the *Law for Protection from Light Pollution*—regulates all outdoor-lighting installations in three northern regions of Chile where major international observatories are located—the second, third and fourth regions—to promote quality lighting and to minimize sky glow.[112] Lighting requirements for outdoor installations outlined in DS686 are described below in Table 5.4. With the implementation of DS686, Chile has become one of the few countries in the world that have national laws regulating outdoor lighting fixtures to reduce the effects of light pollution.

In order to guarantee the execution of DS686, the Office for the Protection of the Skies in Northern Chile (OPCC) was created in May 2000. The Office—which is financed by a consortium that integrates CONAMA with international astronomical organizations such as ESO—provides an interface between the legislative offices of the government and the Chilean public. More specifically, OPCC aims to raise societal awareness of night-sky quality and the negative impacts of light pollution in the northern regions of Chile. It also provides assistance for public agencies that are responsible for implementing the standards outlined in DS686, mainly local municipalities and the Fuel and Electricity Superintendence (SEC). Other

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[112] Allende, *Análisis y proyecciones,* 249; Elizabeth M. Alvarez del Castillo, David L. Crawford, and Donald R. Davis, "Preserving our Nighttime Environment: A Global Approach," in *Light Pollution: The Global View,* ed. Hugo E. Schwarz (Berlin: Kluwer Academic Publishers, 2003), 53; Daud, "Discurso," 6-7.

functions of the Office include providing technical advice to regulate upper-hemisphere light emissions by applying better outdoor-lighting designs; monitoring light pollution in the region; and coming up with legislation improvements by incorporating the voices of the astronomical community, electricity industry, governmental authorities and local communities. More recently in 2002, OPCC was charged with another task: the protection of radio-frequency bands used by telescopes and observatories of radio astronomy.[113] Examples of the work that OPCC has conducted in the northern regions of Chile to help execute the Light Pollution Law are described below.

Table 5.4. Technical requirements for lighting fixtures under DS686

Function	Nominal Lamp Flux (Lumens)	Upper Hemisphere Flux (%)	Lamp Efficacy (Lumens/Watt)	Time Restriction
Roadway	≦15,000	≦0.8%	≧80	None
	> 15,000	≦1.8%	≧80	
Landscaping	≦9,000	≦5%	—	None
	> 9,000	≦1.8%	≧80	
Sports and Recreational	—	—	—	Turned off between 2AM to 6AM (Unless satisfies the requisites for roadways)
Projectors	≦9,000	≦5%	—	None
	> 9,000	≦1.8%	≧80	
Lasers	None	None	None	Aim under horizontal plane between 2AM and 6AM

Source: Pedro A. Sanhueza and Marianela P. Santander, “Protecting the Night Sky of Northern Chile: An Environmental and Cultural Heritage,” in *Light Pollution: The Global View*, ed. Hugo E. Schwarz (Berlin: Kluwer Academic Publishers, 2003).

ii. Lighting Fixtures in La Serena and Vicuña

OPCC has been involved in projects that encourage local authorities to work more closely with lighting professionals to adopt quantitative approaches towards quality

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[113] Daud, “Discurso,” 7-8; Sanhueza and Santandar, “Protecting the Night Sky,” 69-70.

lighting.[114] These projects entail providing technical recommendations for outdoor fixtures so that the light flux is directed to the lower hemisphere, where it is most useful. As shown below in Figure 5.1, fixtures that emit excessive light above the upper-hemisphere flux produce light pollution. By designing and implementing fixtures that emit light within the lower-hemisphere flux, there will be a decrease in the level of light pollution and, simultaneously, an increase in the visibility of nighttime skies. Two of these light-fixture projects have been coordinated in La Serena and Vicuña, both located in Region IV (Coquimbo Region). The measures taken in each of these two municipalities are outlined below.

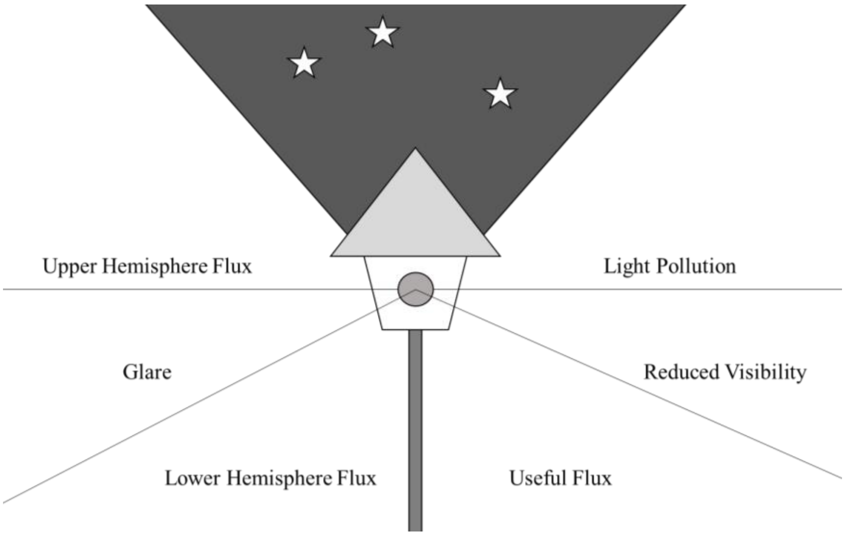

Figure 5.1. Light pollution

Source: Sanhueza and Santandar, “Protecting the Night Sky.”

La Serena

Under the request of OPCC, the Municipality of La Serena agreed to incorporate the lighting requirements outlined in DS686 into municipal master plans. La Serena also opened

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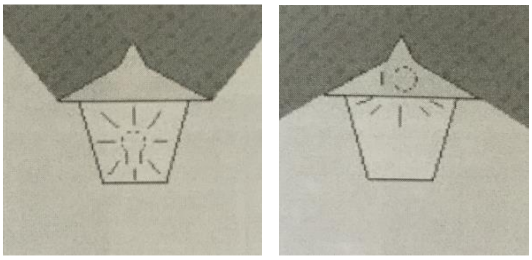
[114] Malcolm G. Smith, “The IAU’s Efforts to Control Light Pollution: Astronomy’s Contribution to an International, Multidisciplinary, Environmental Effort,” in *Light Pollution: The Global View*, ed. Hugo E. Schwarz (Berlin: Kluwer Academic Publishers, 2003), 132.

its financial records of public-lighting expenditures so that practical recommendations could be made for energy savings and pragmatic approaches could be provided to light key areas of the city within the strict confines of the municipal budget.[115] In addition, the municipality embraced the idea of modifying ornamental lighting fixtures located in downtown La Serena. As shown in Figure 5.2, these colonial-style lamps emitted a considerable amount of light above the upper-hemisphere influx. These lamps were redesigned so that lighting fixtures were covered underneath the roof of colonial-style luminaires.[116] These modifications have resulted in lighting efficacy, as displayed below in Table 5.5. The estimated amount of energy being radiated to the upper hemisphere, for example, decreased from 161,000 watts to 11,700 watts—a drop by over 90%.



Before After

Figure 5.2. Modification of colonial-style luminaires in La Serena

Source: Sanhueza and Santandar, "Protecting the Night Sky."

Table 5.5. Quantitative results of lighting modifications in La Serena

	Before modification	After modification
Number of luminaires	-	5,692 modified; 469 new
Increase in the levels of illumination	32,700,000 lumens	58,400,000 lumens (+68%)
Estimated installed power	810,000 watts	660,000 watts (-19%)
Energy radiated to the upper hemisphere	161,000 watts	11,700 watts (-93%)

Source: Sanhueza and Santandar, "Protecting the Night Sky."

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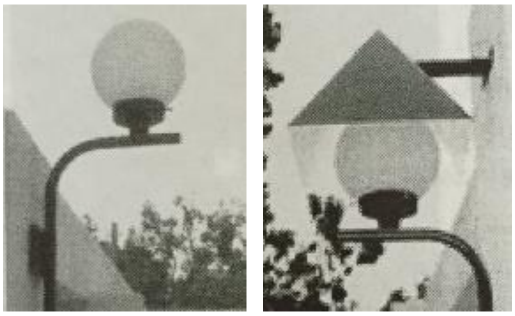
[115] Smith, "The IAU's Efforts," 132-3.

[116] Sanhueza and Santandar, "Protecting the Night Sky," 76.

Technical assistance was also given to Universidad de La Serena for the installation of its new outdoor-lighting fixtures. As shown in Figure 5.3, the outdoor lamps acquired cone-shaped covers to decrease the amount of energy emitted into the upper hemisphere.



Before After

Figure 5.3. Modifications of lighting fixtures in Universidad de La Serena

Source: Sanhueza and Santandar, "Protecting the Night Sky."

Vicuña

In order to comply with the requirements of DS686, advanced lighting experiments have been conducted for selected blocks in Vicuña, a city located near the Cerro Tololo and Gemini South Observatories. Since the late 1990s, Vicuña implemented a large-scale improved illumination system, which include the use of dual LPS and white-light fixtures.[117] Figure 5.4 below shows the modifications that were implemented at Avenida Las Delicias, one of the central streets in the city, to reduce the emission of excessive light and increase lighting efficacy. Table 5.6 also highlights the quantitative effects that these lighting redesigns had on the city of Vicuña. There was nearly a 50% reduction in energy consumption with twice the level of illumination; because the amount of glare was reduced, the light-pollution levels were 25 times lower than the levels before the modifications were taken place.

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[117] Sanhueza and Santandar, "Protecting the Night Sky," 75-6; Smith, "The IAU's Efforts," 133.

Before After

Figure 5.4. Replacement of lighting fixtures at Avenida Las Delicias

Source: Sanhueza and Santandar, “Protecting the Night Sky.”

Table 5.6. Quantitative results of lighting modifications in Vicuña

	Before modification	After modification
Number of fixtures	-	1,534 modified
Increase in the levels of illumination	7,800,000 lumens	8,900,000 lumens (+14%)
Estimated installed power	210,000 watts	110,000 watts (-48%)
Energy radiated to the upper hemisphere	24,000 watts	1,100 watts (-95%)

Source: Sanhueza

3. Recapping the Convergence of Implicit and Explicit Policies in Chilean Astronomy

The implicit policy manifests the local astronomers’ scientific and technological aspirations to place astronomy as the leading field of science in Chile, expand the astronomical community and, in the near future, to establish the Southern Cone country as one of the key players in producing cutting-edge astronomical research. As the voices of local astronomers reveal, the discipline of observational astronomy should be supported and promoted by the government because astronomy—above all the other fields of sciences such as biology and chemistry—could potentially serve as a “pilot test” for future development of science and technology in Chile. The implicit policy, thus, represents the demands of local astronomers to further cultivate the discipline of astronomy in the Latin American country.

Explicit state-led policies that have been implemented since the construction of the first international observatories in Chile seem to meet these demands and converge, directly and indirectly, with the implicit scientific aspirations of Chilean astronomers. The provision of diplomatic and tax-free statuses for all international observatories in Chile, firstly, transformed the country into a type of tax haven for astronomical projects and has made the country into an attractive, cost-effective option for observatories. The Atacama Astronomical Park initiative, along with the promulgation of DS686 and establishment of the Office for the Protection of the Skies in Northern Chile, have also created a favorable environment for international astronomical projects. These institutional and legal frameworks, consequently, have attracted a number of world-class observatories and astronomers to Chile, creating new channels for Chilean astronomers to gain further scientific knowledge and technological expertise. Indirectly, these state-led policies converged with the implicit policy and enabled local scientists to nurture their astronomical community. The government of Chile granted 10% of observation time to all researchers in Chilean institutions via Decree 1766, established the Astronomy Program under CONICYT to oversee the development of Chilean astronomy and increased the amount of grants awarded to astronomical projects. These policy packages have, in a more direct manner, supported the advancement of research conducted by local astronomers, bolstered the capacity of Chilean astronomy and cultivated the development of the local astronomical community. The objectives and contents of these two policies—implicit and explicit—converged, forming a coherent course for the directionality of Chile’s astronomy-related policies.

6. DISCUSSION

1. Theoretical Relevance

Much of the existing scholarship on the development of science and technology in Latin America explores the mechanisms behind the region's lack of innovative dynamism. This sluggish growth in scientific activities has predominantly been explicated by Latin America's peripheral insertion in the international economy and historical dependence on the inflows of foreign science; its structurally-unachieved system of innovation that has failed to integrate relevant actors into the innovation scheme; and the pervasive divergence of explicit and implicit science policies. To a certain extent, these schools of thought elucidate the panorama of Chilean science. Due to Chile's historical reliance on foreign sources of science and technology, the Southern Cone country has not succeeded in cultivating a culture of innovation and, consequently, its science community has remained small. The lack of linkages between academia and the private industry—crucial for the translation of scientific research into technological advancements—has also hindered the development of Chilean science. Moreover, the government of Chile has frequently prioritized the development of economically strategic sectors of science and technology that are not necessarily on the agenda of local scientists and researchers.

Despite the validity of the theories in explaining the overall trends in Chilean science, they seem to lose their soundness when contending with the progress of Chilean astronomy. Let us examine first the "structurally-unachieved innovation system" argument from the perspective of Chile's astronomy program. As the previous sections unpacked, the development of Chile's astronomical capacity has been fueled primarily by universities and the government, along with the collaborative mechanisms formed between these two actors. There were little links between academia and the industry for scientific and technological production, as well as between the government and private enterprises. This implies that scientific research conducted in universities and financially supported by the Chilean government were not captured by private actors for technological development. Yet, the Chilean case presented a unique scientific environment where, instead of local private enterprises playing a role in the national innovation system, the international observatories and projects constructed a mechanism where universities could contribute to scientific and technological development with the knowledge they produce. The high level of scientific research achieved by Chilean universities, thus, were captured and transferred for technological development by the observatories. Although the science-generating structure in Chilean astronomy is missing the industry link and can be portrayed as “structurally unachieved” in the traditional sense of the triple helix of university-industry-government relations, the international observatories and foreign research centers based in Chile have served as an alternate link for the innovation system in astronomy.

It is also necessary to discuss why and how the explicit and implicit science policies in Chilean astronomy converged, dissimilar to many other cases in Latin America that have shown policy divergence. In order to do so, it is crucial to understand the logic behind the explicit state-policies implemented by Chilean officials and analyze why the government 1) directly encouraged research activities conducted by local astronomers and 2) indirectly did so by creating a favorable environment for international astronomical activities. A possible explanation to why the government of Chile directly supported research by local scientists involves the country’s unique and fortunate circumstances. Because the necessary infrastructure and equipment—namely observatories and telescopes—were already set up in the country by international organizations, the only investment the government needed to make in order to develop its astronomical community was in the scientific capacity of its researchers. Although making investments in human resources is often a long and arduous task, the presence of international observatories and world-class equipment in Chile made the development of Chilean astronomy a less costly mission and encouraged the government to offer financial, legal and institutional support for local astronomers. In elucidating why the government indirectly supported the advancement of astronomical research in Chile, it is necessary to first view the southern skies of Chile as its valued natural resource. These southern skies have attracted observatories and astronomical organizations that bring in huge sums of investments into the country; train and develop new generations of qualified local astronomers, which serve as a building block for Chile's knowledge economy; and cultivate a sense of scientific prestige in Chilean society. It is plausible that, to maintain the flow of these benefits, the Chilean government implemented the aforementioned explicit policies that converged with the intellectual aspirations of local astronomers.

As a result of the collaborative mechanisms that cultivated a structurally-achieved innovation system and the convergence of explicit and implicit astronomical policies, Chile's astronomy program has experienced a tremendous level of progress. This "progress" does not refer solely to the growth in local astronomers or increase in the number of cited publications; it denotes how Chilean astronomy has acquired a certain degree of autonomy in terms of scientific research. As the recent experiences of Chilean universities highlight, Chilean astronomy has seen an endogenous process of local scientific forces that develops its own scientific and technological capacities, instead of reproducing the hierarchical relations that keep Chile dependent on the expertise from the global "North." The Chilean experience in astronomy, in other words, nullifies the theoretical explanation that Chile—and Latin America as a whole—is kept dependent on foreign scientific developments.

2. Social Implications of Chilean Astronomy

The development of astronomy in Chile in the recent decades has been manifested in the rapid growth of local astronomers that have increasingly contributed to the publication of research and that have become involved in the development of instrumentation for the international observatories located in Chile. Although this overall increase in productivity and technological expertise of Chilean astronomers should most certainly be highlighted, the implications that this growth in astronomical community had on Chilean society should also be discussed. One major implication that the expansion of local astronomers had entails the development of a government agency dedicated solely to the advancement of science and technology. In April 2013, a group of scientists and research communities presented the government under former President Sebastian Piñera with an open letter requesting that science policy be unified under a single ministry. This petition—which had over 5,000 signatories—was supported by President Piñera, who submitted plans for a ministry that would consist of two sub-secretariats, one for higher education and another for science, technology, and innovation. This appeal represented the demands of Chile's science community, which had, for years, campaigned for the creation of a separate ministry for science and technology. Though the petition was a manifestation of the aspirations of Chile's science community as a whole, the main actor that pushed for a more coherent science policy was the ever-growing astronomical community.[118] Along with the rise in productivity of research activities and the development of scientific and technological knowhow, the new generations of astronomers have brought to the fore the necessity of coordinated science policies and, perhaps more importantly, the value of expanding Chile's scientific capacities.

Another potential impact that the expansion of astronomers had—or is beginning to have—involves the development of Chile's science community. Although data is not yet available, it can be presumed that the enlarging number of local astronomers and increased

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[118] Michele Catanzaro, "Chile puts plan for science ministry on hold," *Nature* 507 (2014): 412-3.

prestige of Chilean astronomy in the global arena will lead to a rise in younger students becoming more interested in pursuing their education in the sciences. Chilean astronomy, hence, has the potential to expand the foundation of scientific talent in Chile and to strengthen its science tradition.

3. Limitations of the Study

Because the development of Chilean astronomy has been a relatively recent progression, it remains uncertain whether Chile will be capable of maintaining this growth in the future and if the findings of this study can be applied to Chile in the long run. This uncertainty stems from the ambiguity of future government support, management capacity and industry linkages. The first—government support—contends primarily with the question of whether the Chilean government will provide sustained assistance to keep the momentum of astronomical research. In order to maintain financial support, for example, Chile would need to increase its R&D investments to reflect the growth of astronomers. Yet, with the declining prices of copper and slow macroeconomic growth that the country has experienced in recent years, the possibility of increasing financial assistance in government-funded astronomy programs appears grim.

The second ambiguity deals with Chile's capacity to manage its astronomy program. Astronomical projects generally involve a number of processes, beginning with the definition of scientific goals, the development and selection of technological designs, construction of the selected design, to the commissioning of the observatories. In addition, these projects involve a large group of researchers and staff that conduct complex scientific procedures. This overall process requires strong leadership and management skills—something that the Chilean government and astronomical organizations may be lacking at this point. If Chile aims to efficiently manage and take greater part in the development of future astronomical projects, the Latin American country would need to gain more experience and bolster its management capacities in overseeing large-scale projects. If the current state of Chile's management capacity is maintained, the tremendous growth that Chilean astronomy has seen in the past few decades may be stifled—and the findings of this research may be too optimistic and can no longer be applicable to the Chilean case. Furthermore, with the expansion of Chile's astronomical community, the management of this emerging group of scientists will become ever more crucial. With the increasing number of Chilean students obtaining postgraduate degrees in astronomy and astrophysics from domestic and foreign universities, Chile needs begin addressing how local institutions and programs can absorb these groups of qualified students. The Chilean government, academic institutions and research centers would need to consider, for instance, providing a larger number of postdoctoral positions with competitive salaries so that the new generation of astronomers can be integrated into Chile's astronomical community. Without instigating such mechanism to absorb astronomers in their formation stages, the positive trajectory of Chilean astronomy may not be sustained.

The third factor that contributes to the uncertainty of the applicability of this study in the long run is the astronomy's link with private industries. As discussed above, there have only been a few cases of partnerships between astronomers and Chilean companies that are involved in the technological development of telescope parts and instrumentation. This lack of interaction between university groups and industry stems from the reality that Chilean industries—especially in the field of astronomy—have not developed to the high standard of quality that astronomical instrumentation requires.[119] It should be noted, however, that the weak linkages between research institutions and private enterprises are not solely characteristic of astronomical studies; it is, unfortunately, a feature of Chile's innovation system and economic structure. The latest data regarding university-industry collaboration for

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[119] Rubio, interview.

scientific and technological development reveals the severity of the situation: in 2008, only 5% of the Chilean companies collaborated with universities and other academic institutions for technological innovation.[120] A Chilean astronomer even quipped that, despite Chile's global standing as the top producer of copper, "[v]ery few things get manufactured in Chile; not even products of copper." The Southern Cone country exports copper—unprocessed and refined—but, because of the lack of technological dynamism emanating from the private sector, imports manufactured products with copper-based components.[121] Although international observatories and foreign research centers based in Chile have so far served as an alternate link for the innovation system in astronomy, it is nevertheless important for local enterprises to strengthen their technological capabilities and initiate collaborations with Chile's emerging astronomy program. Without progress towards university-industry collaborations, it is difficult to determine if Chile would be able to maintain the rapid growth of its astronomical endeavors in the future.

4. Policy Relevance

This study on the development of Chilean astronomy underscores how, despite the institutional obstacles that Latin America has historically encountered in fostering science communities, a culture of endogenous scientific and technological innovation can be cultivated. This finding has major implications for the development of national-level strategies to develop an ecosystem of science and technology not only in the field of astronomy and astroengineering, but also in other disciplines of science. Chile can utilize the lessons obtained from its astronomy program—such as the necessity to acquire a consensus between state-led policies and local scientific aspirations—and the positive experiences it had

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[120] Marcia Varela A. and Lorena Rivera León, "ERAWATCH Country Reports 2012: Chile," *European Commision* (2012): 1-53.

[121] Miguel Roth, interview by author, April 12, 2016.

undergone and translate them to other emerging fields of science. In a broader perspective, this study highlights the possibilities for the development of a research infrastructure in middle-income and developing economies. Whether the country aims to develop a “niche” sector in science like Chilean astronomy or advance its general scientific and technological agenda, the Chilean case sets an example of how emerging economies can take part in the global knowledge system and also encourages these countries to actively pursue their scientific endeavors to boost their innovative capacities.

7. CONCLUSION

Chile’s natural conditions—from dark, cloudless skies to the dry climate of the Atacama Desert—have had a tremendous impact on the development of astronomy in the Southern Cone country. With the establishment of the world’s most ambitious projects in the northern regions of the country, Chile has seen a rapid expansion of astronomy programs in universities, as well as an inflationary growth of local astronomers. Yet, as this paper uncovers, behind the establishment of this “astronomer’s paradise” were a series of collaborations, initiatives and state-led policies that catalyzed the advancement of Chile’s astronomical endeavors. Chilean universities have collaborated, and continues to do so, with numerous foreign universities, research institutions and international observatories to promote graduate training and joint research. This collaborative mechanism has allowed Chile’s astronomical community to capture a large volume of knowledge and expertise in the field, enabling local astronomers to utilize this transferred knowledge to construct new technologies for international observatories based in Chile. Furthermore, the government of Chile has implemented a series of explicit policies that converge, both directly and indirectly, with the implicit aspirations of Chilean astronomers. These policy packages—which include the provision of diplomatic status and tax exemptions to observatories, guaranteed access to telescopes for Chilean researchers, establishment of the Astronomy Program under CONICYT, and regulations to reduce the effects of light pollution in the northern regions of Chile—have supported the development of astronomical research. The convergence of implicit and explicit policies bolstered the capacity of Chilean astronomy and formed a coherent course of directionality of Chile’s astronomy-related policies. This study, moreover, underlines how, despite the institutional obstacles that Latin America has historically encountered in fostering science communities, a culture of endogenous scientific and technological innovation can be cultivated. The findings of this investigation also highlight the possibilities for the development of a research infrastructure in middle-income economies, as well as how these countries can take part in the global knowledge system in the next generations to come.

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APPENDIX

Appendix A. Chronology of major developments in Chilean astronomy

Year	Major development
1849	A scientific mission from the Naval Observatory in Washington D.C. led by Lieutenant James M. Gilliss arrives in Chile with the intention to observe Venus and Mars and to calculate the distance between the earth and the sun. Chile's first astronomical observatory is installed on Cerro Santa Lucia in Santiago de Chile.
1852	The Chilean government purchases the observatory on Cerro Santa Lucia to establish the National Astronomical Observatory (OAN).
1856	The National Astronomical Observatory moves to Quinta Normal District. By 1865, the observatory has achieved a reputation for quality research among fellow researchers in astronomy.
1868	Following Carlos Moesta as the Director of the National Astronomical Observatory, José Ignacio Vergara establishes the Central Office of Meteorology in Chile and begins to study the coordinates of Chilean cities.
1887	The National Astronomical Observatory participates in the production of the "star catalogue"—"carte du ciel"—organized by the International Astronomy Conference, using one of the seven identical Gautier telescopes around the world.
1903	A mission from Lick Observatory in California receives permission to build an observatory on Cerro San Cristóbal, Santiago.
1917	On June 25, the Smithsonian "Solar Constant" Expedition sets up its camp in Calama, Chile. The expedition began in 1917 in North Carolina; yet, because this location turned out to be too cloudy for observation, the expedition began to study climatic conditions in different parts of the world, such as the southern part of Africa, Argentina and Chile. Climatic measurements indicate the Chilean desert to be the least cloudy region and of easy availability; the final location of the expedition is Calama at 2,250 m altitude. Here, the number of cloudless mornings (at 7am), middays (at 2pm) and nights (at 9pm) were 228, 206 and 299, respectively. Temperatures vary between 0 and 25°C.
1927	The National Astronomy Observatory (OAN) becomes part of the Faculty of Physics and Mathematical Sciences at Universidad de Chile, currently located on Cerro Calán, Santiago.
1929	Dr. Manual Foster, former student from the Pontificia Universidad Católica de Chile, acquires the Californian Lick mission observatory and donates it to his former university. The telescope is located on Cerro San Cristóbal. Between 1975 and 1985, the researcher succeeds in extending his field of research to long-term photometric study of stars with varying brightness.
1959	The OAN is transferred from Lo Espejo to its current location on Cerro Calán.
1962	The construction of the Cerro Tololo International Observatory (CTIO) begins and ends five years later. The observatory is inaugurated in 1968.

1965	On April 25, ESO inaugurates the La Silla Observatory on the northern part of Cerro Chinchado in Chile’s Coquimbo Region.
	Universidad de Chile creates its Astronomy Department and starts a Bachelor’s Degree program (Licenciatura).
1971	The observatory at Cerro Las Campanas, which belongs to the Carnegie Institution of Washington, takes up work with its first instrument, the so-called Swope Telescope.
1976	Universidad de Chile creates a Master’s Degree program.
1994	Ronald Mennickent, a recent doctorate of Physics at Pontificia Universidad Católica de Chile, starts an astronomy group when hired by the Physics Department at Universidad de Concepción.
1996	Following Decree n° 26/96, Universidad Católica del Norte launches its new astronomy institute.
1998	In March, Pontificia Universidad Católica de Chile inaugurates its undergraduate program (leading to a Licentiate degree) as the first of its kind in Chile.
	The construction of the first telescope of the VLT Observatory, located on Cerro Paranal at 2,635 m above sea level in the Antofagasta Region is completed. The four telescopes at the Observatory receive names in the Mapuche language: Antu (Sun), Kueyen (Moon), Melipal (Southern Cross) and Yepun (Venus).
1999	Universidad de Chile creates its PhD program in astrophysics.
	Universidad de Valparaíso introduces its new undergraduate program in physics with a major in astronomy.
	The Cosmic Background Imager (CBI) becomes the first radio telescope to be constructed on the Chajnantor plateau. CBI operates until 2010.
2000	The Chilean Society of Astronomy (SOCHIAS) is founded under the direction of L. Bronfman (President) and L. Infante (Vice President and Manager).
	On December 8, the Baade—first of the two 6.5 Magellan telescopes on Las Campanas—is dedicated. First scientific observations begin in February 2001.
2001	Universidad de La Serena opens an undergraduate program in physics with a minor in astronomy.
2002	On January 18, the Gemini South Telescope is inaugurated on Cerro Pachón, near Cerro Tololo.
	The Atacama Submillimeter Telescope Experiment (ASTE) is installed near the Chajnantor Area. This telescope is a pioneer telescope for the NAOJ submillimeter interferometry project (LSA).
	The second Magellan telescope (Clay) begins its scientific operations.
2003	The Atacama Pathfinder Experiment (APEX) is installed in Llano de Chajnantor, 50 km east of San Pedro de Atacama.

2004	In April, the Brazilian SOAR Telescope, an optical and close-range infrared telescope on Cerro Pachón, is inaugurated.
2006	The National Commission for Scientific and Technological Research (CONICYT) creates its Astronomy Program with the intention to promote national development in astronomy and related scientific areas.
2007	The Atacama Cosmology Telescope (ACT) is built on the slope of Cerro Toco at an altitude of 5,200 m.
2009	The 1 m-mini TAO (Tokyo Atacama Observatory) is installed in Cerro Chajnantor at 5,600 m altitude, an area which forms part of the Atacama Astronomical Park.
2011	Universidad Andrés Bello launches its undergraduate program in astronomy.
	Polarbear—built and operated by Berkley with a multinational collaboration of universities and astronomical laboratories—is deployed in Cerro Toco.
2013	Universidad Diego Portales establishes its astronomy program.
2014	Universidad Andrés Bello opens its PhD program in astronomy.

Sources: Jorge E. Allende, *Análisis y proyecciones de la ciencia chilena 2005* (Santiago de Chile: Academia Chilena de Ciencias, 2005); CONICYT, “Astronomy, Technology, Industry”; Matías Gómez, interviewed by author, April 6, 2016; Keiichi Ohnaka, interviewed by author, April 13, 2016; Miguel Roth, interviewed by author, April 12, 2016.

Appendix B. International observatories and telescopes in Chile

Cerro Tololo Inter-American Observatory (CTIO)	
Location	Cerro Tololo, 80 km east of La Serena at 2,215 m altitude
Region	Coquimbo (Region IV)
Land	320 km^2
Land Tenure	Purchased on November 25, 1962
Countries	Chile, United States
Associated Organizations	Association of Universities for Research in Astronomy (AURA)
Telescopes	- 4-m Blanco Telescope opened in 1974 - 1.5-m reflector opened in 1968 - 1.3-m reflector opened in 1997 - 0.9-m reflector opened in 1967 - Yale University’s 1-m reflector, installed in 1973 - University of Michigan’s 0.6-m Wisconsin H-Alpha Mapper (WHAM) telescope - 1.5-m, 1.3-m, 1-m and 0.9-m telescopes operated since 2003 by the Small and Moderate Aperture Research Telescope System (SMARTS) consortium of U.S. institutions - Michigan Orbital Debris Telescope (MODEST) - Panchromatic Robotic Optical Monitoring and Polarimetry Telescopes (PROMPT) array consisting of six 0.4-m telescopes, operated by the University of North Carolina at Chapel Hill since 2006 - 4.1-m Southern Astrophysical Research (SOAR) Telescopes
Funding / Contributions	U.S. National Science Foundation (NSF); National Optical Astronomy Observatory (NOAO); National Radio Astronomy Observatory (NRAO)
Total Investment	US$ 250 million

Sources: Javiera Barandiaran, “Reaching for the Stars? Astronomy and Growth in Chile,” *Minerva* 53 (2015); CONICYT, “Astronomy, Technology, Industry”; Kenneth R. Lang, *A Companion to Astronomy and Astrophysics: Chronology and Glossary with Data Tables* (New York: Springer, 2006); Charles Liu, *The Handy Astronomy Answer Book* (Michigan: Visible Ink Press, 2008); Ian Ridpath, *A Dictionary of Astronomy* (Oxford: University Press, 2012).

La Silla Observatory	
Location	Cerro La Silla at 2,350 m altitude
Region	Coquimbo (Region IV)
Land	825 km^2
Land Tenure	Purchased on December 30, 1964

Countries	Germany, Belgium, Denmark, Spain, Finland, France, Netherlands, Italy, Portugal, United Kingdom, Czech Republic, Sweden, Switzerland
Associated Organizations	European Organization for Astronomical Research in the Southern Hemisphere (ESO)
Telescopes	- 3.6-m reflector, opened in 1976 - New Technology Telescope, an optical/infrared telescope with a 3.58-m mirror whose shape is controlled by active optics, opened in 1989 - 2.2-m reflector jointly owned by the Max-Planck-Institut für Astronomie, opened in 1984 - 1-m Schmidt now operated by Yale University - Danish 1.54-m reflector opened in 1979 - 1.2-m Leonhard Euler Telescope owned by the Geneva Observatory, opened in 2000
Funding / Contributions	ESO
Total Investment	EU€ 200 million

Sources: Barandiaran, “Reaching for the Stars”; CONICYT, “Astronomy, Technology, Industry”; Lang, *A Companion to Astronomy and Astrophysics*; Liu, *The Handy Astronomy Answer Book*; Ridpath, *A Dictionary of Astronomy*.

Paranal Observatory	
Location	Cerro Paranal at an altitude of 2,400 m
Region	Antofagasta (Region II)
Countries	Germany, Belgium, Denmark, Spain, Finland, France, Netherlands, Italy, Portugal, United Kingdom, Czech Republic, Sweden, Switzerland
Associated Organizations	European Organization for Astronomical Research in the Southern Hemisphere
Telescopes	- Four 8.5-m Very Large Telescopes (VLT), which can be operated individually or together as an interferometer - Four 1.8-m Auxiliary Telescopes (ATs), which are used as an interferometric array - Two wide-range telescopes of 2.6 m - 4-m Visible and Infrared Survey Telescope for Astronomy (VISTA) - 2.6-mVLT Survey Telescope (VST)
Funding / Contributions	ESO
Total Investment	EU€ 700 million

Sources: CONICYT, “Astronomy, Technology, Industry”; Lang, *A Companion to Astronomy and Astrophysics*.

European Extremely Large Telescope (E-ELT)	
Location	Cerro Amazonas (20 km from Cerro Paranal) at 2,600 m altitude
Region	Antofagasta (Region II)
Land	180 km^2 and 360 km^2 “reserve”
Land Tenure	Donated by decree 2010 (50-year concession for the reserve)
Countries	Germany, Belgium, Denmark, Spain, Finland, France, Netherlands, Italy, Portugal, United Kingdom, Czech Republic, Sweden, Switzerland
Associated Organizations	European Organization for Astronomical Research in the Southern Hemisphere
Telescopes	39.5-m segmented telescope, which will be the largest optical/infrared telescope in the world when completed in 2018, as scheduled; its main mirror will have an aperture of 42 m and consist of 984 hexagonal segments, each 1.45 m across
Funding / Contributions	ESO
Total Investment	EU€ 1 billion

Sources: Barandiaran, “Reaching for the Stars”; CONICYT, “Astronomy, Technology, Industry”; House of Commons, Science and Technology Committee, *Astronomy and Particle Physics: Fourth Report of Session 2010-12* HC 806 (London: The Stationary Office Limited, 2011); Ridpath, *A Dictionary of Astronomy*.

Las Campanas Observatory	
Location	Cerro Manqui (near Cerro Las Campanas) at 2,280 m altitude
Region	Atacama (Region III)
Land	258 km^2
Land Tenure	Purchased on November 21, 1968
Countries	United States
Associated Organizations	Carnegie Institution of Washington, Harvard University, Massachusetts Institute of Technology (MIT), University of Michigan, University of Arizona
Telescopes	- 6.5-m Magellan Telescopes I and II that began operation in September 2000 and September 2002, respectively - 2.5-m Irénée du Pont Telescope, opened in 1971 - 1.3-m Warsaw University Observatory Telescope, opened in 1996 - 1-m Swope Telescope - 24.5-m Giant Magellan Telescope (GMT) consisting of seven 8.4-m adaptive-optics mirrors being constructed at a foreseen cost of US$ 700

	million in partnership with Australia (Australian National University, Astronomy Australia), South Korea (Korea Astronomy and Space Science Institute) and Brazil; scheduled to begin early operations in 2021
Total Investment	US$ 130 million

Sources: Barandiaran, “Reaching for the Stars”; CONICYT, “Astronomy, Technology, Industry”; Lang, *A Companion to Astronomy and Astrophysics*; Giant Magellan Telescope, “The Giant Magellan Telescope Organization Breaks Ground in Chile,” November 11, 2015, http://www.gmto.org/2015/11/the-giant-magellan-telescope-organization-breaks-ground-in-chile/; Reuters, “Astronomers Begin Work on Giant Chile Telescope,” *Voice of America*, November 12, 2015, http://www.voanews.com/content/astronomers-begin-work-on-giant-chile-telescope/3055186.html; Ridpath, *A Dictionary of Astronomy*.

Southern Astrophysical Research Observatory (SOAR)	
Location	Cerro Pachón at 2,700 m altitude
Region	Coquimbo (Region IV)
Countries	United States, Brazil
Associated Organizations	Brazilian Ministry of Science and Technology (MCT), National Optical Astronomy Observatory (NOAO), University of North Carolina at Chapel Hill (UNC), Michigan State University (MSU)
Telescopes	4.1-m diameter optical/IR-telescope, azimuthal type
Funding / Contributions	Associated organizations
Total Investment	US$ 28 million

Source: CONICYT, “Astronomy, Technology, Industry.”

Gemini South Observatory	
Location	Near the summit of Cerro Pachón at 2,722 m altitude
Region	Coquimbo (Region IV)
Countries	United States, United Kingdom, Canada, Australia, Brazil, Argentina, Chile
Associated Organizations	Association of Universities for Research in Astronomy (AURA)
Telescopes	One of the twin 8.1-m optical/infrared telescopes (Gemini North Telescope is located on Mauna Kea in Hawaii), which has a unique coating chamber that uses “sputtering” technology to apply protected silver coatings on the Gemini mirrors
Funding /	- United States: 43.9%

Contributions	- United Kingdom: 22% - Canada: 13.9% - Australia: 5.7% - Argentina: 2.2% - Brazil: 2.3% - Chile: 10%
Total Investment	US$ 200 million

Sources: CONICYT, “Astronomy, Technology, Industry”; M. Antonieta García Ureta, “Implementing an education and outreach programme for the Gemini Observatory in Chile,” in *Astronomy for the developing world*, ed. John Hearnshaw and Peter Martinez (Cambridge: University Press, 2007); Lang, *A Companion to Astronomy and Astrophysics*; Ridpath, *A Dictionary of Astronomy*.

University of Tokyo Atacama Observatory (TAO)	
Location	Cerro Chajnantor at 5,640 m above sea level in the Parque Astronómica Atacama; highest telescope in the world
Region	Antofagasta (Region II)
Countries	Japan
Associated Organizations	University of Tokyo
Telescopes	- 1-m infrared telescope (MiniTAO) - 6.5-m infrared telescope scheduled to be installed
Funding / Contributions	University of Tokyo
Total Investment	US$ 400 million

Sources: CONICYT, “Astronomy, Technology, Industry.”

Large Synoptic Survey Telescope (LSST)	
Location	Cerro Pachón at 2,680 m above sea level
Region	Coquimbo (Region IV)
Countries	United States
Associated Organizations	LSST Corporation, a consortium of American universities, observatories and research institutions
Telescopes	8.4-m telescope, which will accommodate the world’s largest digital camera with 3.2 billion pixels when completed in 2020, as scheduled; it will be useful for discovering and following objects such as variable stars, novae and supernovae, comets, near-Earth objects, and Kuiper Belt objects, as well as for mapping the distribution of remote galaxies
Funding /	NSF, U.S. Department of Energy and 20 private institutions

Contributions	
Total Investment	US$ 450 million

Sources: CONICYT, “Astronomy, Technology, Industry”; Ridpath, *A Dictionary of Astronomy*.

Atacama Pathfinder Experiment (APEX)	
Location	Llano de Chajnantor, plateau at 5,100 m above sea level in the Atacama Desert
Region	Antofagasta (Region II)
Countries	ESO countries
Associated Organizations	ESO, Max-Planck Institut für Radioastronomie (MPifR), Onsala Space Observatory (OSO)
Telescopes	12-m millimetric and submillimetric antenna, which is the prototype antenna for ALMA; functions at wavelengths between 0.2 and 1.5mm
Funding / Contributions	ESO countries, Max-Planck Institut für Radioastronomie (MPifR), Onsala Space Observatory (OSO)

Sources: R. J. Cohen et al., “Radio-Quiet Zones: Protection of Radio Astronomy Sites,” in *Light Pollution: The Global View,* ed. Hugo E. Schwarz (Berlin: Kluwer Academic Publishers, 2003); CONICYT, “Astronomy, Technology, Industry”; Ridpath, *A Dictionary of Astronomy*.

Atacama Large Millimeter / Submillimeter Array (ALMA)	
Location	Cerro Chajnantor, plateau at 5,100 m above sea level in the Atacama Desert
Region	Antofagasta (Region II)
Countries	United States, ESO countries, Japan
Associated Organizations	National Radio Astronomy Observatory (NRAO), ESO, National Astronomical Observatory of Japan (NAOJ)
Telescopes	66 submillimeter carbon-fiber antennas operating at wavelengths of 0.3 to 3.6 mm and optimized to detect electromagnetic radiation with wavelengths above or below one millimeter; currently the world’s largest and most powerful radio and microwave observatory
Funding / Contributions	United States (NSF), Japan (NINS), ESO countries
Total Investment	US$ 1 billion

Sources: Cohen et al., “Radio-Quiet Zones”; CONICYT, “Astronomy, Technology, Industry”; Liu, *The Handy Astronomy Answer Book*; National Research Council, *The Atacama Large Millimeter Array (ALMA): Implications of a Potential Descope* (Washington, D.C.: The National Academies Press, 2005); Ridpath, *A Dictionary of Astronomy*; Jean L. Turner and Alwyn Wootten, “ALMA,” *Highlights of Astronomy* 14 (2006).

Atacama Cosmology Telescope Project (ACT Project)	
Location	Cerro Toco at 5,400 m above sea level in the Parque Astronómica Atacama
Region	Antofagasta (Region II)
Land	176 km^2
Land Tenure	50-year concession from 2003
Countries	United States, Spain, United Kingdom, Canada, Chile
Associated Organizations	Princeton University, University of Pennsylvania, NASA/GSFC, University of British Columbia, NIST, Pontificia Universidad Católica de Chile, University of KwaZulu-Natal, Cardiff University, Rutgers University, University of Pittsburgh, Columbia University, Haverford College, INAOE, LLNL, NASA/JPL, University of Toronto, University of Cape Town, University of Massachusetts, York College (CUNY)
Telescopes	6-m millimeter-wave telescope designed to map the cosmic microwave background at waves of 2, 1.4 and 1.1 mm
Funding / Contributions	NSF
Total Investment	US$ 100 million

Sources: Barandiaran, “Reaching for the Stars”; CONICYT, “Astronomy, Technology, Industry”; Ridpath, *A Dictionary of Astronomy*.

Atacama Submillimeter Telescope Experiment (ASTE)	
Location	Pampa La Bola in the Atacama Desert at an altitude of 4,860 m
Region	Antofagasta (Region II)
Countries	Japan, Chile
Associated Organizations	National Astronomical Observatory of Japan (NAOJ), Japanese universities from Tokyo, Nagoya, Osaka, Ibaragi and Kobe, Universidad de Chile
Telescopes	10-m submillimeter antenna, which operates at a frequency of 350 and 900 Ghz; used as a prototype for the ALMA construction
Funding / Contributions	NAOJ

Sources: Cohen et al., “Radio-Quiet Zones”; CONICYT, “Astronomy, Technology, Industry”; Ridpath, *A Dictionary of Astronomy*.

NANTEN2 Project	
Location	Llano de Chajnantor, plateau at 5,100 m above sea level in the Atacama Desert
Region	Antofagasta (Region II)
Countries	Japan, Germany, Australia, Switzerland, Chile, South Korea
Associated Organizations	Nagoya University, COSMA (Cologne University), Argelander Institute (Bonn University), ETH Zurich, Radio Astronomic Observatory Seaoul (Seoul National University), Universidad de Chile, University of New South Wales
Telescopes	4-m submillimeter antenna, which operates at frequencies between 115 and 880 Ghz
Funding / Contributions	Nagoya University, COSMA (Cologne University), Argelander Institute (Bonn University), ETH Zurich, Radio Astronomic Observatory Seaoul (Seoul National University), Universidad de Chile, University of New South Wales

Source: CONICYT, “Astronomy, Technology, Industry.”

Polarbear	
Location	Cerro Toco at 5,200 m above sea level in the Parque Astronómica Atacama
Region	Antofagasta (Region II)
Countries	United States, Canada, United Kingdom, France, Japan
Associated Organizations	University of California at Berkley, Lawrence Berkley National Lab, University of Colorado at Boulder, University of California at San Diego, Laborateoire Astroparticule & Cosmologie, Imperial College, KEK, McGill University, Cardiff University
Telescopes	3.5-m Huan Tran Telescope (HTT)
Funding / Contributions	NSF, U.S. Department of Energy (Office of High Energy Physics); NSERC; Science and Technology Facilities Council (European Union Marie Curie), Miller Institute for Basic Research in Science (James B Ax Family Foundation)
Total Investment	US$ 8.4 million

Source: CONICYT, “Astronomy, Technology, Industry.”

Cornell Caltech Atacama Telescope (CCAT)	
Location	Cerro Chajnantor at 5,612 m above sea level in the Parque Astronómica Atacama

Region	Antofagasta (Region II)
Countries	United States, Canada, United Kingdom, Germany
Associated Organizations	Cornell University, California Institute of Technology (with Jet Propulsion Laboratory), University of Colorado, University of British Columbia (for a Canadian university consortium), U.K. Astronomy Technology Centre (on behalf of the United Kingdom), universities of Cologne and Bonn
Telescopes	25-m submillimeter antenna, which is expected to be in operation in 2017 and function as a wide-field survey instrument to complement the observation at ALMA
Funding / Contributions	Cornell University, California Institute of Technology, University of Colorado, University of British Columbia, U.K. Astronomy Technology Centre, universities of Cologne and Bonn
Total Investment	US$ 110 million

Sources: CONICYT, “Astronomy, Technology, Industry”; Ridpath, *A Dictionary of Astronomy*.

Cosmology Large Angular Scale Surveyor (CLASS)	
Location	Cerro Toco at 5,200 m above sea level in the Parque Astronómica Atacama
Region	Antofagasta (Region II)
Countries	United States
Associated Organizations	Johns Hopkins University, NASA Goddard Space Flight Center
Telescopes	Survey telescope
Funding / Contributions	NSF, Johns Hopkins Unversity
Total Investment	US$ 7 million (US$ 5 million from NSF)

Source: CONICYT, “Astronomy, Technology, Industry.”